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Title: Investigation of the Environmental Impacts of Wind Energy and Supplemental Energy Systems using a Life Cycle Approach

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Wind energy is a promising alternative energy source due to its environmental, economic, and social benefits and, as such, has garnered public support and government incentives for its development and implementation. With the growing number of wind parks in Oregon, a life cycle assessment (LCA) study for a representative new wind park is needed to investigate the potential impacts on the environment. One of the major drawbacks of wind energy generation is its variability due to the stochastic nature of wind. To make wind energy a more reliable source, wind energy generation should be supplemented with controllable energy generation or storage. Thus, the aim of this research is to improve the understanding of the effects of supplemental energy systems on the environmental impacts of wind energy systems. First, the environmental impact of a single wind turbine is examined from raw material extraction to the end of life stage. Research needs are identified to support the assessment of the environmental impacts of wind energy and supplemental energy systems from a life cycle perspective. Next, supplemental electricity generation systems investigated are biomass, hydro, and natural gas electricity generation, and zinc-bromine battery storage. Finally, the results for each system are compared to coal energy generation. It appears that the wind park has lower environmental impact than coal energy generation when paired with any of the complimentary systems investigated. Overall, hydropower appears to be the best option to supplement wind power from an environmental perspective for a potential wind park site in northern Oregon.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Preedanood Prempreeda, Author

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CONTRIBUTION OF AUTHORS

Dr. Karl R. Haapala assisted in the writing and analysis of all manuscript. Dr. Ted Brekken assisted in the analysis of wind power and battery storage inventory. Gorka R. Asensio aided in the development of the methodology and wind data generation for Manuscript 2. Alexander A. Bistrika and Chianna Alexander aided in zinc-bromine battery's material inputs.

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LIST OF ACRONYMS

AO	Agricultural Land Occupation
BPA	Bonneville Power Administration
CCE	Climate Change Ecosystems
CCH	Climate Change Human Health
CO	Colorado State
CO_2	Carbon Dioxide
E	Egalitarian Archetype
ED	Ecosystem Diversity
EIA	Energy Information Administration
FD	Fossil Depletion
FE	Freshwater Ecotoxicity
FEU	Freshwater Eutrophication
GHG	Greenhouse Gas
H	Hierarchist Archetype
HH	Human Health
HT	Human toxicity
I	Individualist Archetype
IL	Illinois State

LIST OF ACRONYMS (Continued)

IR	Ionizing Radiation
ISO	International Organization for Standardization
KY	Kentucky State
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MD	Meter Depletion
ME	Marine Toxicity
NC	North Carolina
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NT	Natural Land Transformation
OD	Ozone Depletion
PA	Pennsylvania State
PM	Particulate Matter Formation
PO	Photochemical Oxidant Formation
PTFE	Polytetrafluoroethylene
RA	Resource Availability

LIST OF ACRONYMS (Continued)

SMES	Superconducting Magnetic Energy Storage
TA	Terrestrial Acidification
TE	Terrestrial Ecotoxicity
THF	Tetrahydrofuran
UO	Urban Land Occupation
VA	Virginia State
WD	Water Depletion
ZnBr	Zinc-Bromine Battery

CHAPTER 1 – INTRODUCTION

This chapter gives a background and motivation for the research undertaken. It describes the research problem and thesis objectives and provides an outline for the thesis.

1.1 Motivation for the research

Coal, petroleum, natural gas, and other fossil fuels have traditionally been the leading sources of electric power generation in the United States. However, the combustion of fossil fuel is accompanied with various kinds of impact on the environment, e.g., greenhouse effect, ozone depletion, and air pollution. Both the environment and people are endangered by such impact, e.g. due to coastal flooding due to increased levels of sea-water and eco-system damage due to increasing atmospheric temperature [1]. As a result, renewable energy has been introduced to reduce the usage of fossil fuel.

Renewable energy sources are considered as clean sources of energy and optimal use of these resources will minimize environmental impacts, produce minimum secondary wastes, and be environment sustainable based on current and future economic and societal needs [2]. Renewable energy systems do not emit significant greenhouse gas emissions in the generation of electricity. However, there are considerable emissions associated with the material procurement, manufacturing, and transportation activities throughout the life cycle of renewable energy systems.

Wind energy is one of the leading renewable energy sources and the fastest growing in electricity production. Wind energy is a promising renewable source due to its environmental, economic, and social benefits, and has garnered public and governmental support for its development in the United States. This research is motivated by the premise that wind energy represents an economical and technically feasibly option for future electricity production. However, wind power is intermittent and unreliable as a stand-alone system [3] . If wind energy is integrated with a supplemental energy or energy storage system, this limitation can be overcome and the supplemental energy can be efficiently utilized through the high efficiency wind energy system.

1.2 Problem statement

Renewable energy sources like solar or wind energy offer a solution to substitute for coal or nuclear generated power. Nevertheless, wind power is inherently intermittent and fluctuating. It generally requires some form of energy storage or supplemental energy where a fairly steady supply of electricity is expected.

Due to the developing nature of wind energy systems, and the need for supplemental energy, the environmental impacts of wind energy are uncertain. In order to assess these impacts, the life cycle assessment (LCA) method can be applied. LCA is a evaluation method that facilitates the collection of data about inputs and outputs to and from the product system and the environmental performance of these inputs and outputs

[4]. When conducting a life cycle assessment, the environmental impacts of interest and the stressors that result in these impacts must be identified. The production of these stressors is inventoried throughout all life cycle stages within a defined system boundary.

1.3 Research objectives

The research presented herein serves several objectives to address the problem statement. The first objective is to investigate the environmental impact of a single wind turbine from raw material extraction to the disposal stage. This will help identify the research needs to support the second objective which is to assess the environmental impacts of wind energy and supplemental energy systems from a life cycle perspective. The third objective is to assess the environmental impacts of wind energy and energy storage using the life cycle assessment approach. This work aims to improve understanding of the effects of supplemental energy systems on the environmental impacts.

1.4 Thesis outline

The research in this thesis is reported in the form of multiple manuscripts, and composed of six chapters. The current chapter (Chapter 1) provides the motivation behind the research conducted in this thesis, gives a description of the research problem under investigation, and outlines the thesis objectives and chapter flow. Chapter 2 provides a literature review of prior work related to life cycle assessment and wind energy. The literature covered in the chapter focuses on recent literature, i.e., 2000-2011, but traces back to the early 1970s for a more complete review. Chapter 3, the first manuscript, focuses on the environmental impact of a single wind turbine using the life cycle assessment approach. Chapter 4, the second manuscript, concentrates on the LCA of supplemental energy to assist wind energy during its down times to ensure a stable electrical energy load. Also, this chapter compares the environmental impact of supplemental energy to the impacts of coal power. Chapter 5, the third manuscript, focuses on the LCA of wind park using energy storage to reduce wind power fluctuations. The result is compared with coal based electricity generation. Chapter 6 summarizes and concludes the research discussed in previous chapters. Recommendations for future work are also discussed to improve on the findings and carry the research forward.

CHAPTER 2 – LITERATURE REVIEW

Today, 86% of the energy consumed in the United States comes from fossil fuels, e.g., coal, petroleum, and natural gas, with crude oil-based petroleum as the dominant source of energy [5]. Renewable energy resources supply a relatively small but steady portion (about 8%) of U.S. total energy consumption, relatively low compared to the portion of fossil fuel energy consumption. Because fossil fuels are a non-renewable resource, the world's energy dependence on their consumption is not a sustainable practice. When considering renewable energy, wind energy accounts for the most rapid growth in terms of installed capacity [6]. Wind power can provide energy while reducing carbon dioxide (CO_2) emissions [7]. Therefore, use of wind power may help mitigate climate change and avoid regional environmental problems brought about by burning coal [8].

The objective of this literature review is to introduce how wind energy can be evaluated using environmental life cycle assessment. This literature review will focus on the strengths and weaknesses of prior research; additional literature relevant to ensuing chapters is reviewed within each chapter (manuscript). Second, the availability of wind power will be reviewed, in order to propose options to ensure the reliability of wind power. Finally, energy storage technologies will be reviewed to introduce their benefits and recent trends.

2.1 Introduction to life cycle assessment

Life cycle assessment (LCA) is a method to quantify the environmental impacts of a product or process, across its entire life (cradle to grave) [9]. LCA started with the undertaking of studies that aimed to optimize energy consumption which represented a restraint for industry [10]. In order to improve the analysis, LCA took energy use into account from raw material consumption to disposal. The first study commonly thought of as an LCA study was for the Coca Cola Company in 1969 [11]. The study compared resource consumption and environmental releases associated with different beverage containers.

Life cycle assessment guidelines and examples have been established by the International Organization for Standardization (ISO) 14040 family of standards [12]. The main advantage of LCA is supporting decision making with scientific data. Life cycle assessment consists of four stages as follows (Figure 2.1) [10–16]:

1. Goal and scope definition: This step provides a description of the product system in terms of the system boundaries and a functional unit. This stage also defines the functional unit, system boundary, assumptions, and limitations.

The system boundary determines the processes that will be considered in the life cycle analysis. The functional unit defines what precisely is being studied and quantifies the service delivered by the product system, providing a reference to which the inputs and outputs can be related (e.g., hours of light provided by a light bulb).

2. Life cycle inventory (LCI): In the life cycle inventory phase of an LCA, all relevant data are collected and organized. Without an LCI, no basis exists to evaluate comparative environmental impacts or potential environmental improvements. The level of accuracy and detail of the collected data is reflected throughout the remainder of the LCA process. The data will be gathered directly from companies, utilities, and other organizations or from available databases.

3. Life cycle impact assessment (LCIA): The focus of this step is to provide indicators and the basis for analyzing the potential contributions of the resource extractions and emissions contained in the LCI to potential impacts. LCIA qualitative process to characterize and assess the effects of the environmental interventions identified in the inventory analysis. LCIA evaluates the potential human health and environmental impacts of the environmental resources and release identified during LCI.

4. Life cycle interpretation: Life cycle assessment interpretation, or improvement analysis, is a systematic procedure to identify, qualify, check, and evaluate information from the conclusions of the inventory analysis and/or impact assessment, and to present them in order to meet the requirements of the application describe in the goal and scope of the study. ISO defined life cycle interpretation as the step that reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phase of LCA [10].

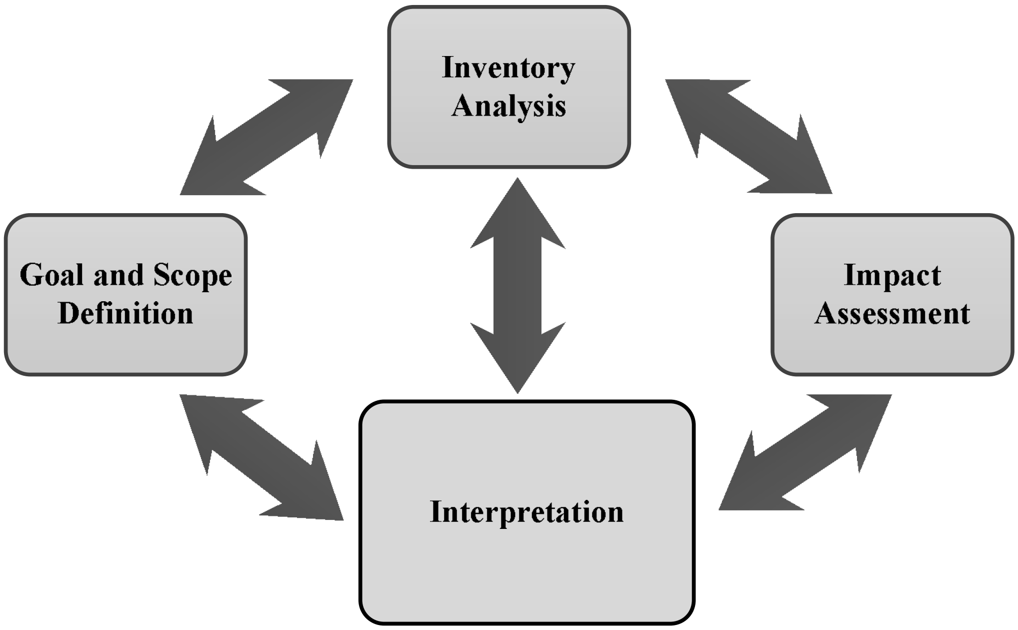

Figure 2.1 Life cycle assessment processes [10]

Overall, LCA is a complex evaluation method that facilitates the collection of data about inputs to outputs from the product system, as well as the assessment of environmental performance of these inputs and outputs [4]. LCAs are normally done in a static way, meaning that a fixed generation portfolio (coal, nuclear, gas, wind, solar, etc.) underlies the energy production. LCA can identify opportunities to improve the environmental performance of products at various points in their life cycle and inform decision makers in industry, government or non-governmental organizations.

Concerns over the limitations of LCA are still raised in present. Guinee et al. [10] stated the limited scope of LCA is the insufficiently accounted for when using the results. It can be limited in geographical coverage (dominated by Europe and North America), in feedstocks covered, in the number of different emissions to the environment included, and in environmental impacts. Another concern is the translation from functional unit to real world improvements. This may be the most difficult issue to address. Side effects such as indirect land use, rebound effects, market mechanisms, and suchlike all play a role in how a large-scale production of biofuels would affect the food market, scarcity, social structure, land use, nature, and other things that are important for society [4]. In the near future, regionalized databases of LCA will develop with new impact assessment methods and improved methods for uncertainty analysis.

2.2 Life cycle impact assessment methods

Life Cycle Impact Assessment (LCIA) is essentially meant to improve the understanding of the results of the life cycle inventory (LCI) phase. LCIA transforms inventory data into information about the environmental impacts from the product system. At the same time, it reduces the inventory's numerous data items into a limited collection of impact scores. This involves modeling the potential impacts of the inventory results and expressing them as impact scores that can be added within each category. LCIA has to be interpreted or weighed. The life cycle impact assessment methodology may include a weighting method to aggregate LCA results into easily understandable numbers or units. Many methodologies have been suggested and described. Several are introduced below.

2.2.1 The Eco-indicator 99 impact assessment methodology

The Eco-indicator 99 impact assessment methodology was developed under the authority of the Dutch Ministry of Housing, Spatial Planning and the Environment. It developed based on the Eco-indicator 95 method. Eco-indicator 99 has defined three types of damage to the environment, caused by eleven impact categories [17]:

1. Human Health: This damage type considers the number and duration of diseases and life years lost due to premature death from environmental causes. Associated impact categories include climate change, ozone depletion, carcinogenic effects, respiratory effects, and ionizing radiation.

2. Ecosystem: This damage type considers the effect of process inputs and outputs on species diversity, especially for vascular plants and lower organisms. Associated impact categories include ecotoxicity, acidification, eutrophication, and land use.

3. Resource availability: This damage type considers the surplus energy needed in the future to extract lower quality mineral and fossil resources. Associated impact categories include the depletion of agricultural and bulk resources under the land-use.

Eco-indicator values are reported in terms of points (Pt), which facilitate the comparison of relative differences between the products or systems analyzed. The value of 1 Pt is representative of one thousandth of the yearly environmental load of one average European inhabitant [17]. This value was calculated by dividing the total environmental load in Europe by the number of inhabitants and then multiplying it by the scale factor of 1000 [17].

2.2.2 ReCiPe 2008 impact assessment methodology

ReCiPe 2008 is the most recently develope life cycle impact assessment method. Similar to Eco-indicator 99, the primary objective of the ReCiPe method is to transform the long list of life cycle inventory results into a limited number of indicator scores [18]. ReCiPe 2008 harmonized the Eco-indicator 99 with the CML 2002 method together.

ReCiPe 2008 provides a "recipe" to calculate life cycle impact category indicators. It comprises two sets of impact categories, which are at the midpoint and endpoint level, with associated sets of characterization factors [18]. Eighteen impact categories are addressed at the midpoint level (parentheses indicate abbreviations used in the work), which are fossil depletion (FD), metal depletion (MD), natural land transformation (NT), urban land occupation (UO), agricultural land occupation (AO), marine ecotoxicity (ME), freshwater ecotoxicity (FE), terrestrial acidification (TA), climate change human health (CCH), climate change ecosystems (CCE), terrestrial ecotoxicity (TE), ionizing radiation (IR), freshwater eutrophication (FEU), particulate matter formation (PM), photochemical oxidant formation (PO), water depletion (WD), human toxicity (HT), and ozone depletion (OD) [19]. At the endpoint level, most of these midpoint impact categories are further converted and aggregated into three endpoints, which account for damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA).

Each level (midpoint, endpoint) can be weighted according to three cultural perspectives developed using cultural theory. These perspectives, or archetypes, represent a set of an individual's choices on issues like time horizon or expectations that proper management or future technology development can avoid future damage, as follows:

1. E (Egalitarian): Long time perspective; even a minimum of scientific proof justifies inclusion into impact weightings.

2. I (Individualist): Short time perspective; only proven effects are included in weighting impacts. The attitude of an individualist considers each limit as negotiable.

3. H (Hierarchist): Balanced time perspective; consensus among scientist determines inclusion of effects.

The H (Hierarchist) archetype is normally chosen as the default weighting set because impacts are backed up by scientific and political bodies with sufficient recognition. ReCiPe 2008 allows for valuation similar to the Eco-indicator 99 method.

2.3 Energy storage technology

Energy storage is an enabling technology for meeting renewable portfolio standards and reliability needs. Energy storage would improve the reliability and dynamic stability of the power system by providing stable, abundant energy reserves that require little ramp time and are less susceptible to varying fuel prices or shortages [20]. Energy storage can shift the energy produced to the required load level, allowing generators to run more efficiently at a stable power level, potentially decreasing the cost of electricity [21].

The following content is intended to provide background information on the operation of storage devices. Since there are a number of conventional secondary battery technologies and flow batteries used for energy storage, those technologies will be the focus of the following discussion and summarized from [22–27].

Supercapacitors: A supercapacitor, or ultracapacitor, or double-layer capacitor has a very high capacitance. Supercapacitors are mainly used to level out power quality fluctuations within a timeframe between a few seconds and minutes. The energy is stored as electrostatic energy. The charge characteristic is similar to an electrochemical battery and the charge current is, to a large extent, limited by the charger [28].

The disadvantage of a supercapacitor is the discharge curve because the voltage of the supercapacitor decreases on the linear scale from full to zero voltage which reduces the useable power spectrum and much of the stored energy is left behind [26]. Rather than operating as a stand-alone energy storage device, supercapacitors work well as low-maintenance memory backup to bridge short power interruptions [28].

Superconducting Magnetic Energy Storage: Superconducting Magnetic Energy Storage (SMES) could be used for various timeframes, but is currently only produced for power quality purposes [23]. The energy is stored as electromagnetic energy in superconducting magnets, which need to be cooled down to extremely low temperatures. The conductor for carrying the current operates at cryogenic temperatures where it becomes superconductor and, thus, has virtually no resistive losses as it produces the magnetic field. Consequently, the energy can be stored in a persistent mode, until required. The efficiency of SMES systems is high (around 95%). The disadvantage of SMES is the need to maintain operating temperatures which requires the refrigeration unit and high power [29].

Flywheels: Flywheels can be used to store the excess energy in the form of kinetic energy. They work by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy [22]. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy [22]. Adding energy to the system correspondingly results in an increase in the speed of the flywheel. Flywheels also show a high efficiency with a low maintenance rate. A limitation for flywheel is energy storage time. Flywheel energy storage systems use mechanical bearings, which mean they can lose their energy over time [30].

Zinc-Bromine Batteries: Zinc-bromine (ZnBr) batteries are a type of hybrid flow battery, in which electrodes are separated from the energy storage liquid. A solution of zinc bromide is stored in two tanks. If the battery is charged, zinc is plated on the electrode and vice versa [31]. Operation is described in detail in Chapter 5. ZnBr batteries are well suited for long-term energy storage. A zinc-bromine battery can be left fully discharged indefinitely without damage. It has the ability to store energy from any electricity generating source [32].

Compressed Air Energy Storage: The idea behind compressed air energy storage is to use the excess energy to pressurize an underground reservoir with air. If energy is needed, then it is released. As the operation of the battery, the compressor will decouple from the turbo expander which produces the power [23]. The energy can be stored over a long timeframe. The major disadvantage of CAES facilities is their dependence on geographical location. It is difficult to identify underground reservoirs where a facility can be constructed, which is close to the electric grid, able to retain compressed air, and large enough for the specific application [21].

Pumped Hydropower: Another energy storage option for long-term storage is pumped hydropower. It consists of two large reservoirs located at different elevations and a number of pump/turbine units. During off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed [33]. Hereby, excess energy is used to pump water to a higher location and thus store the energy as potential energy. Once required during peak electrical production the water in the upper reservoir is released through the turbines, which are connected to generators that produce electricity [33]. Various sites with pumped hydropower exist throughout the world. The ultimate drawback is its dependence on specific geological formations with sufficient area [34].

In general, the use of energy storage with electricity generation increases the input energy required to produce electricity, as well as the total greenhouse gas (GHG) emissions due to the production of battery. Despite this increase of GHG, the life cycle GHG emissions from storage systems when coupled with nuclear or renewable sources is substantially lower than from fossil fuel derived electricity sources [21].

2.4 Life Cycle Assessment of Wind Energy

Several life cycle assessment studies of wind energy systems have been reported. The review will point out the strengths and weaknesses of existing environmental analysis work in the area of wind energy. The purpose is to identify the potential deficiencies in prior LCA studies of wind energy for future research.

The earliest LCA study of wind energy identified in the literature investigated the impact of a single wind turbine on the environment [35]. The generator size (500 kW) of the investigated turbine was much smaller than today's modern wind turbines. Schleiner [35] presented a model to assess energy and emissions from the production and manufacture of material using LCA. Jungbluth et al. [36] compared solar cells and wind turbines (< 800kW). Weinzettel et al. [37] investigated floating wind turbines for an offshore project. The main focus was on marine ecotoxicity. Capacity factor, which is the ratio of actual delivered energy to theoretical maximum energy over a period of time, was used to estimate energy production of the power plant as presented in many studies [37-39]. Pehnet [38] investigated the effects on the life cycle impacts by considering the energy portfolio changes over the lifetime of the turbine (20 years).

Vestas [39] conducted a LCA on a 2.0 MW wind turbine from a manufacturer perspective. The Vestas study has a comprehensive material inventory due to the scope covered from cradle to grave.

Lenzen and Munksgaard [40] assessed 72 previous energy and CO_2 analyses of wind turbines for both on-land and offshore systems around the world including the U.S., U.K., Germany, Denmark, Switzerland, Belgium, Argentina, Brazil, Japan, and India. Their research found that due to differences in assumptions (e.g., load factors and number of years of wind farm operation) and in the chosen scope and boundaries of the studies (e.g., including transportation, construction and decommissioning), the country of manufacture, and power ratings of the different turbines, the results of these 72 studies demonstrated considerable variation. Energy intensity, defined as required energy invested in the system for manufacture, transport, per unit of electricity produced over its life cycle, was found to vary from 0.014 to 1 kWh. Carbon dioxide intensity, that is, the mass of CO_2 emitted per unit of electricity produced over the life cycle, was found to vary from 7.9 to 123.7 g CO_2/kWh. The main motivation came from a study done by Lenzen and Wachsmann [41]. They investigated the location dependence of assessments for renewable sources. The study compared locations in Brazil and Germany, and came to the conclusion that LCAs are highly location dependent.

2.5 Reliability of wind power

Wind energy is considered as a green energy technology because it has only minor negative impacts on the environment compared to conventional energy. Wind energy does not release emissions like thermal power plants that rely on combustion of fossil fuels and thus it does not produce atmospheric emissions that cause acid rain or global warming [41]. However, Inhaber [42] reported several disadvantages of wind energy based on studies of wind farms around the U.S. These disadvantages include poor reliability, thus requiring backup energy storage, intermittency, and variability. Inhaber suggested that replacing a fossil fuel power plant with a wind farm will not reduce the current ambient level of carbon dioxide in the atmosphere. Options to ensure the reliability of a wind energy system include the following [42]:

1) Back up generation capacity
2) Long distance transmission lines
3) Extensive energy storage capacity

Economic profitability of wind energy is of concern, and has been investigated by Wang et al. [43]. Net Present Value (NPV) was used to estimate the profit from wind energy. Wang et al. stated that installing a large number of wind turbines reduces the overall efficiency of the wind farm. The result was a new optimization tool that handles areas of different surface roughness for each wind direction and transmission line capacity.

2.6 Limitations of prior work

Environmental impact and energy security concerns have resulted in an increasing number of life cycle assessment studies of fossil fuel energy and renewable energy. Global warming has been directly attributed to the carbon dioxide emissions in the combustion of fossil fuels, a key source of electrical energy today [44]. Wind energy is considered to be a promising alternative energy source due to its economic, environmental and social benefits [45]. Nevertheless, its uncertainty due to the stochastic nature of wind reduces the reliability of electricity produced, which is considered to be one of the major drawbacks of wind energy [46].

A review of the literature found limited LCA studies of wind energy in the U.S. Table 2.1 shows the literature studies identified for different regions around the world. These LCA studies were either focused only on the wind turbine itself or on a generic assumed energy production of a wind park. Thereby, the studies are limited in their validity for specific locations. Thus, there is a need to perform LCA studies for different locations within the U.S. Due to this location dependence, it was of interest to investigate the environmental impacts for a wind park in northern Oregon (Columbia River Gorge) using LCA.

Table 2.1 Summary of prior wind energy LCA studies by region

Location	Study Goal	Sources
The Americas	Compare three wind turbine models	[47]
	Compare the environmental impacts and net-energy inputs of two stand-alone small wind turbine systems	[48]

	Determine GHG emissions of onshore and offshore wind power	[49]
	Determine GHG emissions of a wind-fuel cell integrated system	[50]
	Determine the impact of geographical variation of a wind turbine production's location	[41]
	Determine the environmental impacts of a wind farm using Eco-indicator 99 method	[51]
	Determine the environmental impact of an offshore wind farm in Florida	[52]
Europe	Compare offshore and onshore wind farms to assess energy use	[35]
	Compare photovoltaic and wind power for the production of energy	[36]
	Evaluate the environmental burden of floating offshore wind turbine	[37]
	Study CO_2 emissions of offshore wind energy	[38]
	Study the environmental impact of a wind turbine from cradle to grave	[39]
	Determine CO_2 emission of wind turbines using LCA	[40]
	Determine the environmental impact of a 2 MW wind turbine using the CML method	[53]
	Review LCA studies of wind turbines to identify research need	[54]
	Determine environmental impact of wind turbines using Eco-indicator 99 method	[55]
	Determine environmental impacts of a 2MW wind turbine	[56]
	Perform sensitivity study on LCA result of 2MW wind turbine	[57]
	Compare two different designs of 2.0 MW wind turbines to determine the environmental impacts	[58]
	Compare two models of wind turbines	[59]
	Compare GHG emissions of wind and hydropower	[60]
	Determine the environmental impacts of a wind farm and identify energy consumption of the wind farm	[61]

	Determine the environmental impacts and cumulative energy demand of a wind turbine	[62]
	Determine the environmental impact of a150 MW offshore wind park	[63]
	Determine the environmental impact of an offshore wind park using alpha ventus method	[64]
Asia	Determine the environmental impact of a wind park in Fuzhou, China	[65]
	Determine CO_2 emissions of a wind park	[66]
	Review LCA studies of wind turbines to determine the LCIA method used	[67]

As can be seen from the table, prior work has not examined the system level effects of using supplemental energy systems with wind energy systems. Solutions to ensure the reliability of wind power plant are studied herein. This investigation is divided into three studies. The first (Chapter 3) study the environmental impacts of 2.0 MW wind turbines. The second investigates potential supplemental energy generation sources, which can be integrated with wind energy systems (Chapter 4). The third study investigates energy storage to supplement wind energy during low wind energy states (Chapter 5).

The disadvantages of wind energy create challenges in advancing the use of wind energy. In this research, the main focus will be on investigating the effect of supplemental and energy storage systems on wind energy system environmental impacts. However, many open questions remain to be solved and elaborated. These include education, awareness, and mutual learning, as well as suitable and easily accessible tools and appropriate international databases, which are needed for a broader proliferation of life cycle assessment methodology for accurately evaluating wind energy systems for engineering and policy decision making.

CHAPTER 3 – COMPARATIVE LIFE CYCLE ASSESSMENT OF 2.0 MW WIND TURBINES

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Abstract

Wind energy is a clean form of energy and produces virtually no emissions during operation, however, environmental impacts occur across the entire life cycle of a wind turbine. The work presented herein examines the environmental impacts of two 2.0 MW wind turbine models from a life cycle perspective. Life cycle stages including manufacturing, transport, installation, maintenance, and disposal have been considered for both models and are compared using the ReCiPe 2008 impact assessment method and energy payback analysis as conducted based on the cumulative energy demand produced by the wind turbines over 20 years. The assessment revealed that environmental impacts are concentrated in the manufacturing stage. The energy payback periods for the two turbine models are found to be 5.2 and 6.4 months, respectively. Based on the assumptions made, the results of this study can be used to conduct an environmental analysis of a representative wind park to be located in northern Oregon.

3.1 Introduction

Due to fossil fuel based electricity production, greenhouse gases and carbon dioxide emissions are released into the environment. A 2012 report from the U.S. Energy Information Administration (EIA) showed that 3.6Gt of carbon dioxide was released into the atmosphere in 2011, mainly from burning fossil fuel, a rise of 1.6Gt over 2009 [5]. Increasing concerns and awareness of carbon emissions as well as costs and security issues surrounding fossil-based energy have led to the exponential growth of renewable energy, including wind energy generation [6]. The U.S. EIA has predicted that renewable energy consumption in the electric power sector will grow from 1477 PJ in 2010 to 3587 PJ in 2035, with wind accounting for 44 percent of the growth [5]. Figure 3.1 shows the growth of installed wind energy capacity in Oregon from 2001 to 2011 [68].

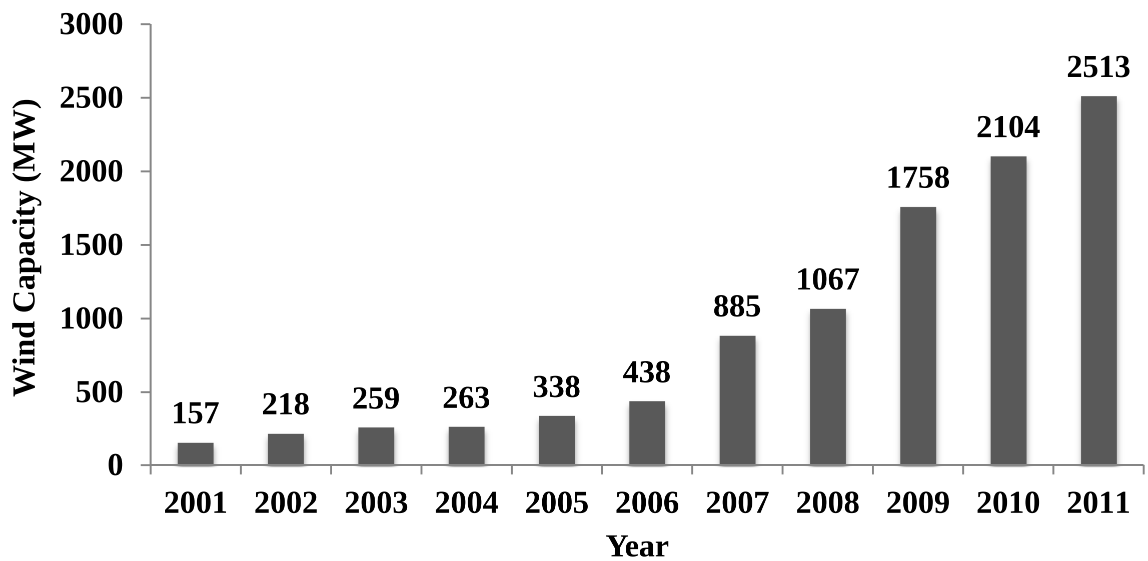

Figure 3.1 Wind capacity from 2001 to 2011 in Oregon [68]

Wind energy is one of the most promising alternative energy sources [54]. During operation, wind power plants are friendly to the environment, releasing no direct emissions and requiring little energy consumption. The majority of environmental impacts of wind power plants occur during the manufacture and installation processes [69]. All systems for converting energy into usable forms have various environmental impacts, not to mention a requirement of natural resources. It is essential to have consistent evaluation methods for analyzing all aspects of a given energy source. Without such methods, it is difficult to compare them and make the right decisions when planning and investing in energy systems [70].

A life cycle impact assessment approach is therefore important in order to identify the environmental burdens associated with the life cycle of wind power plant. Life cycle assessment (LCA) is a method to assess the environmental impacts of a product from raw material acquisition through production, use, and end-of-life [10], [15]. Life cycle assessment guidelines have been established by the International Organization for Standardization (ISO) 14000 family of standards [10].

LCA studies for wind energy have been conducted to investigate many aspects (Table 3.1). The following section will briefly review prior LCA studies related to wind energy. Weinzettel et al. investigated modernized turbines for an offshore project [37]. The authors used the CML 2 baseline 2000 V2.03 method and presented the environmental impacts for eight different impact categories. The main focus was on marine eco-toxicity. Generic capacity factors were assumed to estimate energy production. Lenzen and Wachsmann [41] reported the only work identified in a review of the literature that focused on transportation of wind turbine components from the manufacturer to a specific wind park location in the analysis.

Prior studies have considered various environmental impacts. Some present only greenhouse gas emissions [47], [60], [61]. Ardente et al. [61] described emissions of seven different air emissions, seven water emissions, and three kinds of solid wastes. Schleisner [35] reported seven different emissions types. Tremeac et al. [59] used a method called Impact 2002+ that links 14 midpoint impact categories to four damage types: climate change, resources, ecosystem quality, and human health [59]. Methodology dependence was investigated for the same study assumptions by using different impact assessment methodologies, giving significantly different results. Martinez et al. conducted two studies with same wind turbine by using different methods. One used the Eco-Indicator 99 method using 11 different impact factors [56]. The other used the CML methodology which reports environmental impact in 10 different impact categories presented as equivalents of different emissions [53].

The LCA methodology applied during the course of these studies has been and is still evolving, including the development of impact assessment methods. Clearly, using different methodologies can cause widely different results. Use of the different methodologies makes it difficult to compare assessments to each other and raises questions about whether studies using different methodologies should be compared at all. In addition, it is difficult to assess the breadth of technical improvements driven by LCA results due to the fact that LCA results are often used for marketing purposes [39].

It can be seen that there is a limited number of LCA studies of wind turbines in the U.S. (Table 3.1). Most wind energy LCA studies are based in Europe, which has likely been a direct consequence of the higher number of wind energy installations in Europe - approximately 50% more than in the U.S. Thus, a key motivating factor for the research reported herein is the limited amount of reported LCA studies for wind turbines installed in the US.

The objective of the work reported herein is to perform a comparative LCA for two potential wind turbines to be deployed in a representative wind park located in northern Oregon. First, the goal and scope of the study are presented. Next, supporting LCI data and process models are reported. Then, the results of the life cycle impact assessment are presented and discussed. Finally, based on this study, several conclusions are drawn.

Table 3.1 Summary of prior wind energy LCA studies by location

Location	Study Goal	Sources
The Americas	Compare three wind turbine models	[47]
	Compare the environmental impacts and net-energy inputs of two stand-alone small wind turbine systems	[48]
	Determine GHG emissions of onshore and offshore wind power	[49]
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	Determine the environmental impacts of a wind farm using Eco-indicator 99 method	[51]
	Determine the environmental impact of an offshore wind farm in Florida	[52]
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	Determine environmental impact of wind turbines using Eco-indicator 99 method	[55]
	Determine environmental impacts of a 2MW wind turbine	[56]
	Perform sensitivity study on LCA result of 2MW wind turbine	[57]
	Compare two different designs of 2.0 MW wind turbines to determine the environmental impacts	[58]
	Compare two models of wind turbines	[59]
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	Determine the environmental impacts of a wind farm and identify energy consumption of the wind farm	[61]
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	Determine the environmental impact of an offshore wind park using alpha ventus method	[64]

Asia	Determine the environmental impact of a wind park in Fuzhou, China	[65]
	Determine CO_2 emissions of a wind park	[66]
	Review LCA studies of wind turbines to determine the LCIA method used	[67]

3.2 Research methodology

In order to assess relative environmental impacts and identify potential future research needs of wind energy generation, the life cycle assessment (LCA) method was applied. The LCA study was facilitated using a commercially available software tool (SimaPro 7.3). In general, an LCA study is completed in four stages: (1) Define the goal and scope, (2) Conduct a life cycle inventory analysis, (3) Conduct a life cycle impact assessment, and (4) Interpret the results [10]. These stages are described below.

3.2.1 Goal and scope definition

The goal of this study is to compare the life cycle environmental impacts of two wind turbine designs. This LCA study has been developed with the future goal of determining and quantifying the impacts wind energy production. The two turbines, eventually to be located in northern Oregon, are 2.0 MW onshore wind turbine models, referred to as Model 1 and Model 2. Both models have similar function and technical specifications, but differ in design and performance characteristics.

The scope definition of an LCA provides a description of the product system in terms of the system boundaries. The scope of this study is from cradle-to-grave and considers the raw material extraction, wind turbine manufacturing, transportation of wind turbine to the site, operation and maintenance, and dismantling and recycling (Figure 3.2). Transformers and substations are not included. The wind turbine lifetime was assumed to be 20 years. The functional unit is a reference unit which provides a clear, full and definitive description of the product or service being investigated, enabling subsequent results to be interpreted correctly. Thus, the functional unit for this LCA study is defined as a 2.0 MW wind turbine which assumes the two models are functionally equivalent. The energy payback comparison also considers the amount of energy generated over its 20 year life time.

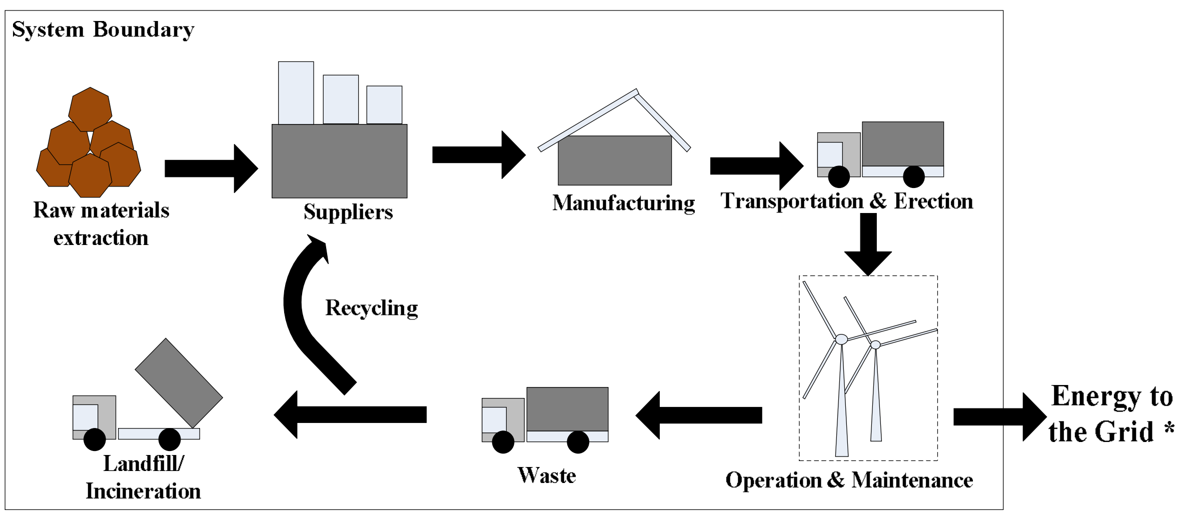

Figure 3.2 Scope of the LCA (*considered in energy payback analysis)

3.2.2 Life cycle inventory

Wind turbines consist of many mechanical and electrical assemblies, which are comprised of many sub-components. Therefore, it is a challenge for practitioners to gather the information from all suppliers that provide the wind turbine components. Information contained in the life cycle inventory (LCI) is described below.

Wind turbine characteristics: Model 1 is a 2.0 MW, three bladed, upwind pitch regulated wind turbine with active yaw control [71]. The blades are 39 m in length with full span control and a four-part modular tower of 78 m in height. The rotor operates with a speed of 1900 rpm. Model 2 is also a 2.0 MW turbine and has been designed for medium and low wind sites [72]. The blade is 40 m in length and the design employs a three-part modular tower that is 78 m in height.

Wind turbine components: To compile the life cycle inventories for the wind turbines, the systems were decomposed into their major assemblies, sub-components, and respective materials. The paint used in the rotor, nacelle, and tower is excluded as this information was not available. Other minor components such as bolts, fasteners, and internal wires are also neglected. A material description for each model is presented in Table 3.2. Information about the various sub-systems is provided below.

Rotor: Rotor is the part onto which the blades are mounted. The rotor assembly consists of three blades, hub, nose cone, and bearing.

Nacelle: The nacelle of a wind turbine is the box-like component that sits atop the tower and is connected to the rotor. The nacelle housing is made of fiberglass and protects the internal components from the environment. The nacelle cover is fastened to the main frame, which also supports all the other components inside the nacelle [39]. The main frames are large metal structures that must be able to withstand large fatigue loads. Nacelle components include the nacelle cover, gearbox, generator, hydraulic system, main shaft, and yaw/pitch system.

Tower: The nacelle assembly is mounted on top of a high tower to allow the blades to take advantage of the best winds. Towers are typically made of tubular steel sections coated with paints and sealants and joined by flanges and bolts [39].

Foundation: The tower is attached to the foundation with a base flange by screwed rods cast into concrete or bolted to an embedded tower section.

Table 3.2 Wind turbine materials and masses

Components	**Model 1** [71]		**Model 2** [72]	
	Material	**Total Mass (tons)**	**Material**	**Total Mass (tons)**
Rotor Assembly	Steel	5.00	Steel	5.40
	Fiberglass	7.50	Carbon fiber	3.69
	Epoxy	5.00	Fiberglass reinforced plastic	7.96
	Cast iron	8.50	Cast iron	8.50
Tower	Steel	200.00	Steel	165.00
Nacelle Assembly	Steel	12.27	Steel	25.63
	Copper	2.50	Copper	2.34
	Silica sand	0.15	Aluminum	0.54
	Cast iron	35.92	Cast iron	16.47
	Fiberglass reinforced plastic	2.00	Fiberglass reinforced plastic	6.40
	Lubricant (20 years)	300.80	Lubricant (20 years)	601.60
Foundation	Steel	35.00	Steel	38.00
	Concrete	775.00	Concrete	750.00
Total Mass (ton)		**1389.64**		**1631.53**

Wind turbine operation and maintenance: According to manufacturer information, regular inspection visits are made three times a year using a diesel truck [39], [49]. Change of oil, lubrication and transport to and from the turbines is included in the stages of operation and maintenance .Maintenance of rotor blades and gears is required once within a lifetime. One replacement generator has been provided for during the complete lifetime of the wind turbine [39].

Transportation: Transportation impacts result from emissions caused by the extraction and production of fuel and the combustion of fuel during transport. Transportation of materials, components, and assemblies to the turbine manufacturer has been neglected due to the inability to trace the complete supply chain. Each component is instead assumed to be transported to the wind park site from the component manufacturer by road truck, measured in tkm (ton-kilometers). The unit tkm is equivalent to the transport of one ton (1000 kg) product over one kilometer. A 50% load factor is used to account for trucks transporting turbine parts to the wind site and returning to the manufacturer empty. Table 3.3 presents the distance from the wind turbine component suppliers to the wind park location (Augspurger, Oregon).

Table 3.3 Transportation distances from supplier to wind park site

Component	**Model 1 Supplier** (Distance, km)	**Model 2 Supplier** (Distance, km)
Blades	Edensburg, PA (4229 km)	Windsor, CO (1945 km)
Rotor	Fairless Hills, PA (4200 km)	Brighton, CO (1931 km)
Gearbox	Verona, VA (4464 km)	Lake Zurich, IL (2782 km)
Generator	Raleigh, NC (3826 km)	Raleigh, NC (3826 km)
Yaw/Pitch system	Andalucia, Spain (8722 km)	Hebron, KY (3181 km)
Tower	Fairless Hills, PA (4200 km)	Pueblo, CO (2205 km)
Nacelle	Fairless Hills, PA (4200 km)	Brighton, CO (1931 km)

Dismantling and recycling: The end of life stage is an important aspect of the life cycle assessment. The recycling rates of materials are adopted from previous studies [39], [57], [59], [64], [66]. Steel, copper, aluminum, and cast iron recycling rates are at 90%, and non-recyclable waste is transported to a landfill. Concrete is not recycled, so it assumed to be landfilled entirely (left in ground). It is assumed that the recycling location is 50 km from the wind park. Material end of life is show in Table 3.4.

Table 3.4 Type of dismantling [39], [53], [63]

Material	**Type of dismantling**
Iron	Recycling with a loss of 10%
Fiberglass	Landfill 100%
Steel	Recycling with a loss of 10%
Concrete	Landfill 100%
Copper	Recycling with a loss of 5%
Plastics	Incinerated 100%
Rubber	Incinerated 100%
Oil	Incinerated 100%

3.2.3 Life cycle impact assessment method

This study presents a LCA of 2 MW wind turbine and using two methods in analysis are ReCiPe 2008 and energy payback time. The LCA is modeled using SimaPro, a software tool for LCA.

The environmental impacts of wind turbines were compared using ReCiPe 2008 method version 1.03 with a world weighting set across three different archetypical perspectives (i.e., Egalitarian, Hierarchist, and Individualist). The ReCiPe Midpoint method evaluates the impact to eighteen categories as follows: fossil depletion (FD), metal depletion (MD), natural land transformation (NT), urban land occupation (UO), agricultural land occupation (AO), marine ecotoxicity (ME), freshwater ecotoxicity (FE), terrestrial acidification (TA), climate change-ecosystems (CCE), terrestrial ecotoxicity (TE), ionizing radiation (IR), Freshwater eutrophication (FEU), particulate matter formation (PM), photochemical oxidant formation (PO), water depletion (WD), human toxicity (HT), ozone depletion (OD), and climate change-human health (CCH). One exception for water depletion (WD) category is not taking into consideration in SimaPro software, so this category will be represent as zero. One thousand ReCiPe points is equivalent to the environmental impact generated by one European citizen over the course of a year [18].

Energy payback is used to measure how long a system has to operate to generate enough energy to offset the amount of energy required during its entire life [58]. It is calculated as the ratio of total primary energy requirements of the system throughout its life cycle to annual electricity generated. For a wind turbine, it can be defined as the cumulative cradle-to-grave energy requirement divided by the annual energy generated by the wind turbine [37]. Here, the cumulative energy requirements comprise energy for production, transport, maintenance, and decommissioning.

3.3 Life cycle assessment result

Life cycle assessment results are first presented for the ReCiPe 2008 method. The results are then analyzed using sensitivity analysis. Finally, energy payback periods are calculated for each model used.

Figure 3.2 presents the comparison of overall environmental impact between wind turbine Model 1 and Model 2 for each archetype. The egalitarian (E), hierarchist (H), and individualist (I) perspectives were applied to elucidate the effect of different weighting sets on the results. It shows that Model 1 has significantly greater impact than Model 2. The Egalitarian perspective weights the impact of Model as 50% for Model 1 and 45% for Model 2 of the total damage, while the Hierarchist weights it as 30% for Model 1 and 33% for Model 2 and Individualist as 20% for Model 1 and 22% for Model 2. The different perspectives provide similar conclusions with respect to other alternatives and then the concern associated with using different archetypes can be reduced.

As seen in Figures 3.3(A) and 3.4(A), the environmental impacts of the wind turbines are mainly from the manufacturing stage. The manufacturing stage includes the transportation from component manufacturer to the wind site. The impacts are greater than maintenance stage impacts by 75% for Model 1 and 85% for Model 2. Interestingly, the end of life stage produces negative environmental impact, reflecting a benefit to the environment of recycling iron, steel, and copper.

Figures 3.3(B) and 3.4(B) show the relative environmental impacts of the wind turbine components. It is seen that the relative impacts are similar for components of both models. The tower is the key contributor to the environmental impact (40%), followed by the rotor (27%), nacelle (25%), and foundation (8%), respectively. Significant proportions of impact for several components are due to fossil depletion. Steel is the primary material in the tower, and the majority of fossil depletion results from steel processing for the tower.

Despite the significant amount of materials used, final impact is reduced by 28% because of the 90% material recycling. Under the assumptions made in this study, however, benefits would still be realized in each case.

With the life cycle inventory analysis complete, the impact assessment proceeded by finding the impact contributions of the material inputs using ReCiPe 2008. The results (Figure 3.6) reveal that steel is the predominant material in terms of environmental impact. Steel has the greatest impact on Model 1. While reinforcing steel has the greatest impact on Model 2.

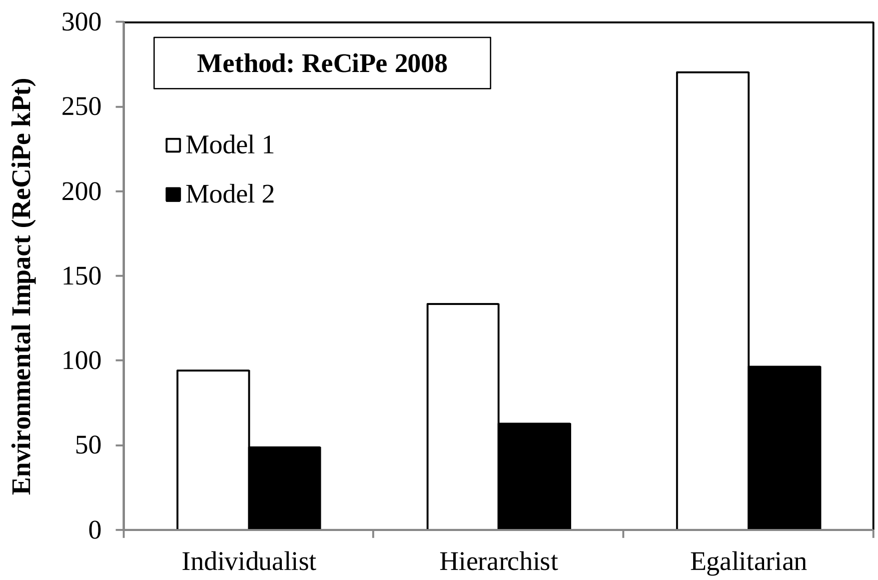

Figure 3.3 Comparison of environmental impacts under different archetypes.

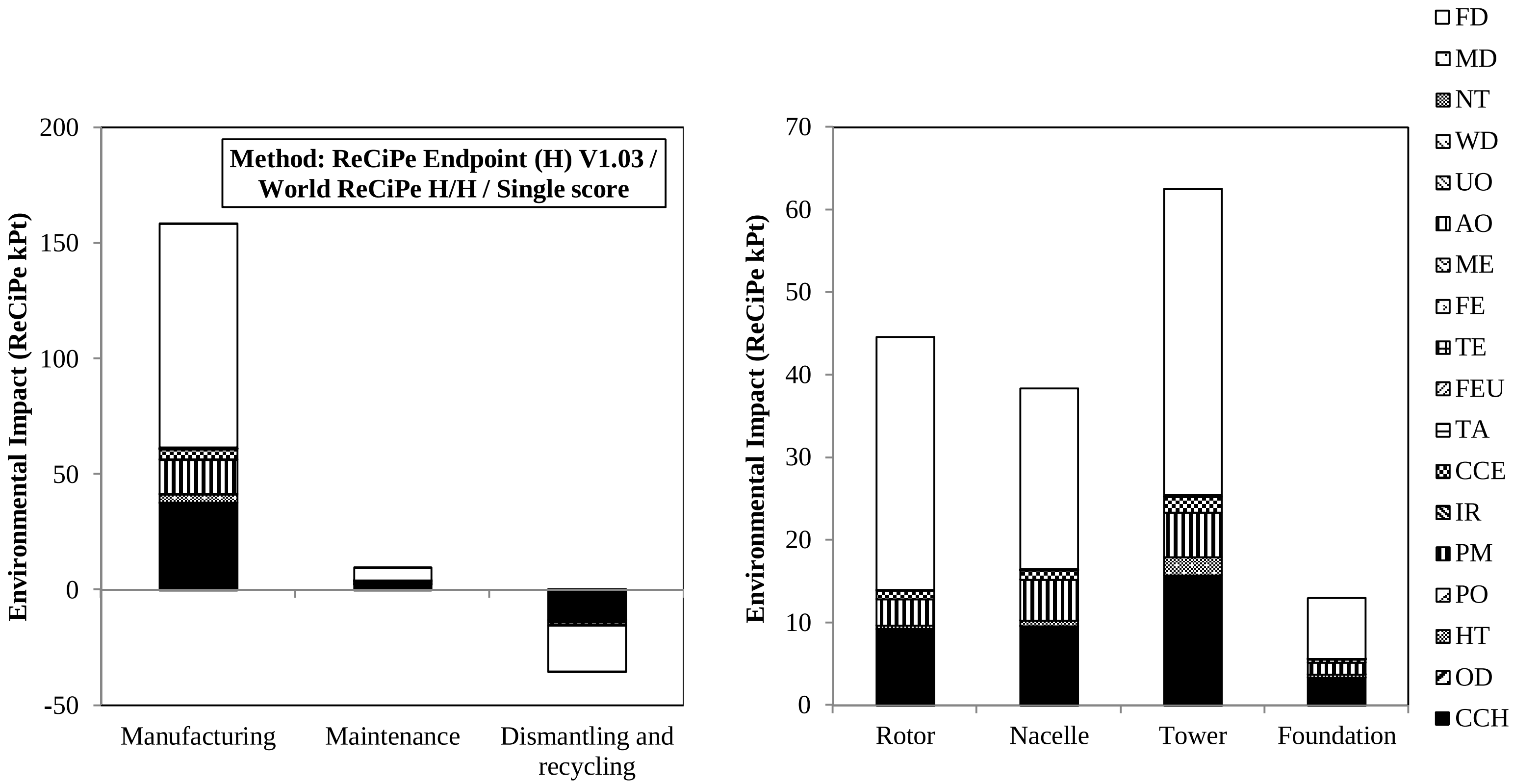

Figure 3.4 Environmental impact of Model 1 for (A) Cradle to grave life cycle stages and (B) Major components.

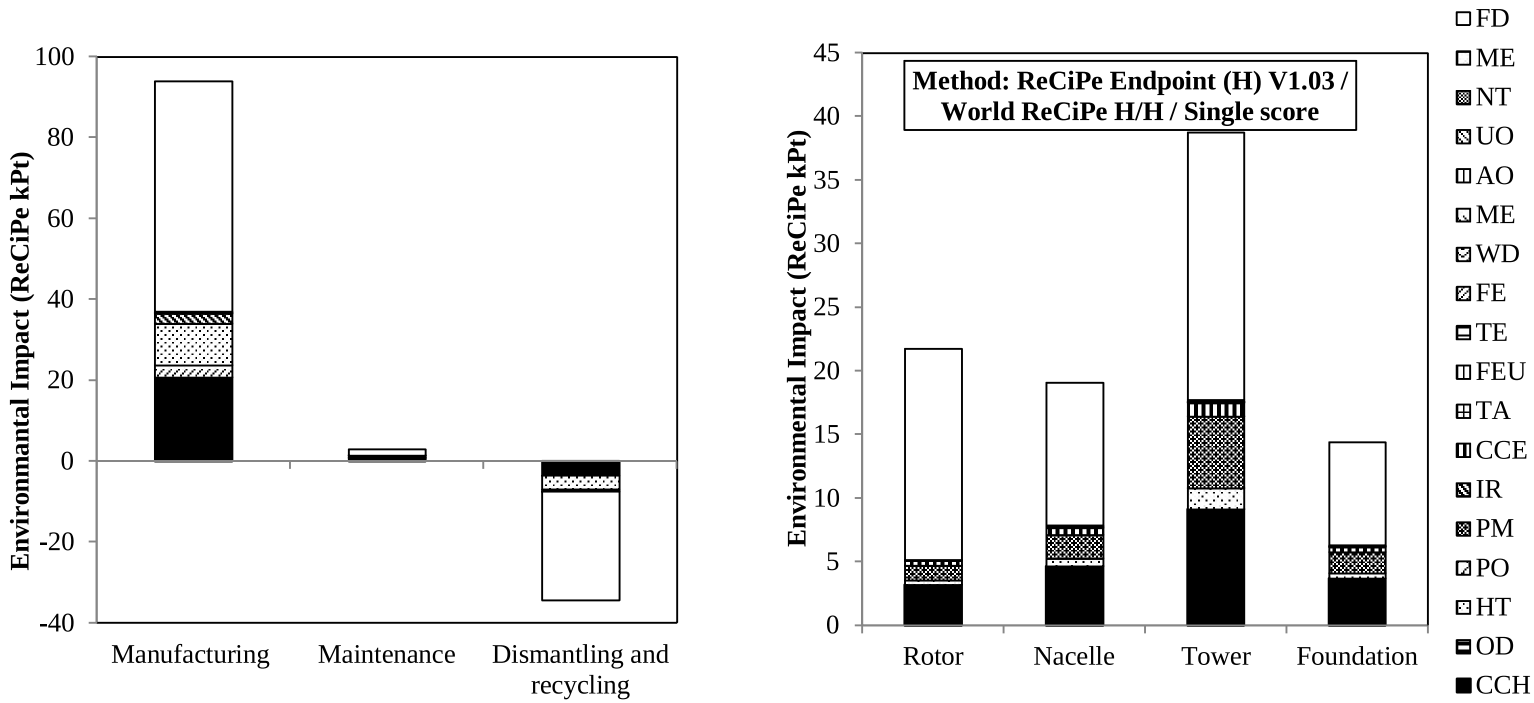

Figure 3.5 Environmental impact of Model 2 for (A) Cradle to grave life cycle stages and (B) Major components

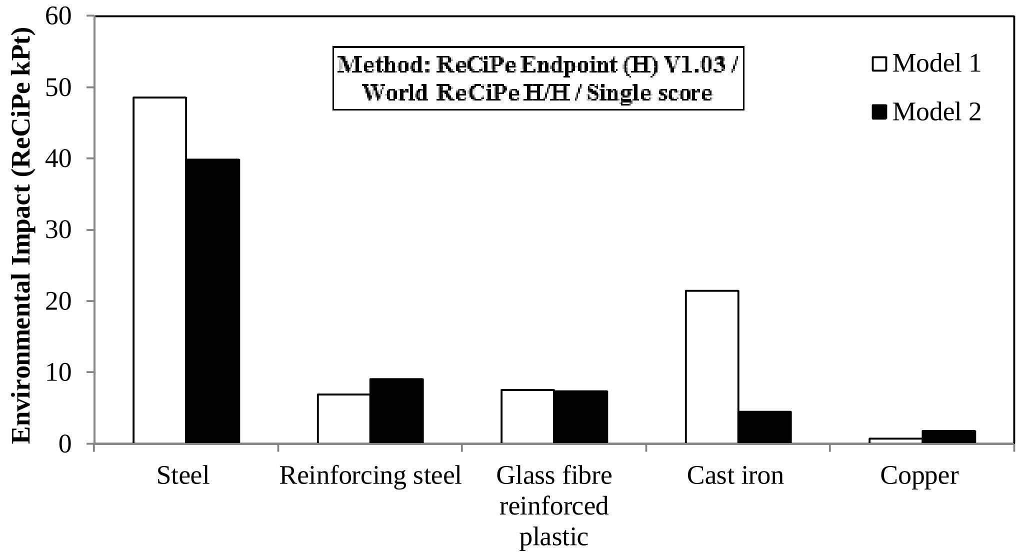

Figure 3.6 Environmental impact of material inputs for each wind turbine

3.4 Interpretation

Inventory data are critical in determining the success of an LCA study. Thus, the uncertainties arising from the assumptions made during the development of the LCA have been analyzed using three scenarios: SC1 assumes an increase in maintenance over the wind turbine lifespan, SC2 assumes an increase in the percentage of recycled material to 100%, and SC3 assumes a change in transportation type from truck to freight rail. The need to conduct scenario analysis is to assess the sensitivity of the environmental impacts to the assumptions made in each stage.

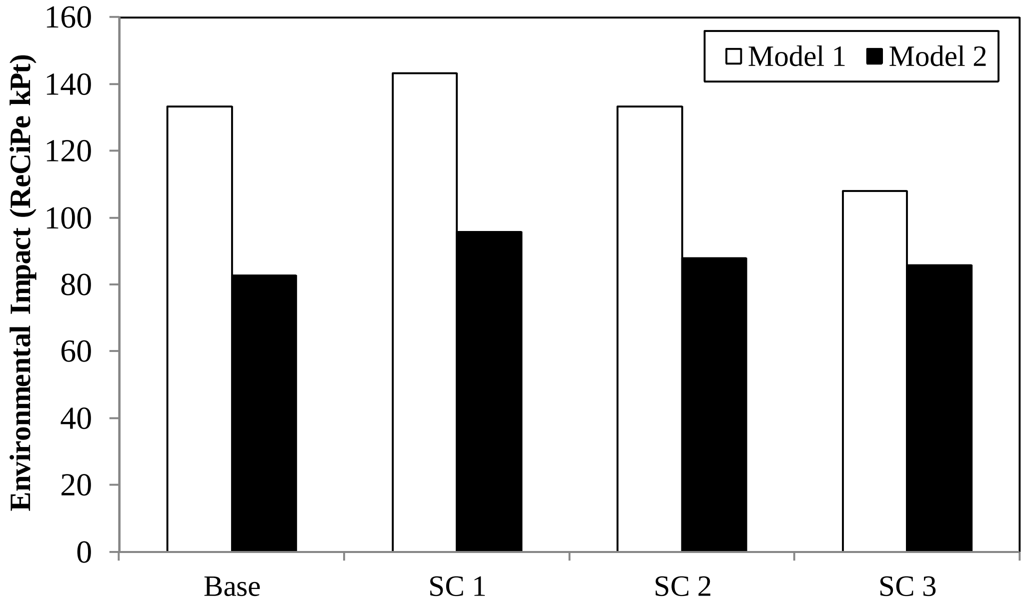

Figure 3.7 Environmental impacts of each scenario for the wind turbine models considered

The sensitivity analysis conducted shows variations in the overall impact (Figure 3.7). Increasing maintenance (SC 1) has the greatest effect on the overall environmental impact, resulting in an increase of 7.2 % (Model 1) and 12.5% (Model 2). The environmental impact of transportation changes (SC 3) for Model 2 increases by 6%, which contrasts with Model 1 (a reduction of 5%). Surprisingly, increasing the percentage recycled (SC 2) did not significantly affect the environmental impact for either wind turbine. Moreover, sensitivity in the results was less than typical uncertainty in LCA studies (20%). Thus, the conclusion that Model 2 is the superior option holds.

The energy payback time is an important indicator for renewable resources. For this purpose, the impact assessment method called Cumulative Energy Demand is used. It gives a result which includes the total energy used across the whole life cycle of an analyzed product or process. It is assumed that a 2.0MW wind turbine generates 6.13 GWh per year with a 35% capacity factor. Energy payback time for Model 1 is 5.2 months and Model 2 is 6.4 months.

3.5 Conclusions

This LCA compared the environmental impacts of two wind turbines. The tower, rotor, and nacelle are found to contribute most to the environmental impact in each case. For the tower, the large amount of steel required is the major contributor to cradle to grave impact. One of the outcomes from this LCA study is the confirmation that the main life cycle environmental impacts originated from the production of the turbine. In addition, it was shown that the use stage has an almost negligible environmental impact. It is found that recycling is important to the environmental profile of the turbine, while transportation type can have a profound effect on life cycle impacts.

The end of life stage represented a benefit to the overall impact. Without recycling there was an increase in impacts for each category. Model 2 was found to be superior in environmental performance and is suitable for the proposed wind power plant. The main difference between the two models is the design of the tower.

Model 1 is a four-part modular tower, while Model 2 uses a three-part tower module. Model 1 requires 35 tons more steel than Model 2.

When compared to prior work, the results lead to a similar conclusion that environmental impacts are driven by the material consumption, especially steel. In addition, the transportation distances of wind turbine components to the wind park site also influenced environmental impact. The travel distance of Model 1 is longer than Model 2 by 16,000 km (approximately 50%), and some components are transported from other continents for Model 1.

This study investigated the life cycle environmental impacts of wind turbines in the U.S., which addresses a limitation of prior studies. The results of this study, however, are in agreement with prior studies. Due to the rapid growth in energy demand in recent years, it is important to invest in renewable energy technologies to achieve more sustainable energy. The results from this study may aid in promoting sustainable energy technologies and policies to support wind energy development. Specifically, it is shown that energy developers should consider not only the functional characteristics of a wind turbine, but also the materials, component and system design, and the supply chain needed to manufacture, construct, and decommission a wind turbine.

CHAPTER 4 – ENVIRONMENTAL IMPACT OF WIND ENERGY IN NORTHERN OREGON - PART 1: SUPPLEMENTAL ENERGY GENERATION

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Abstract

Wind energy is a promising alternative energy source due to its environmental, economic, and social benefits and, as such, has garnered public support and government incentives for its development and implementation. According to the U.S. National Renewable Energy Laboratory (NREL), Oregon has the potential for over 27,000 megawatts of installed onshore wind power. With the growing number of wind parks in Oregon, a life cycle assessment (LCA) study for a representative new wind park has been performed, with available supplemental energy sources also considered. The location of the wind park was selected based on predicted energy generation for several sites in northern Oregon using data from the Bonneville Power Administration (BPA) and information from a wind turbine manufacturer. One of the major drawbacks of wind energy generation is its variability due to the stochastic nature of wind, thus, biomass, natural gas, and hydropower are examined as potential supplemental energy sources, using an LCA approach. Environmental impacts are compared to those for coal-based energy, which would be replaced by the new system. From the analysis, each of the three options would result in lower impacts than coal energy generation. It appears that hydropower would be the least impactful option to supplement wind power from an environmental perspective.

4.1 Introduction

As governments, corporations, and consumers become increasingly aware of the environmental impacts caused by electricity production from fossil fuel, renewable energy has gained importance in producing electricity. Renewables are considered clean sources of energy, and optimal use of these resources can lower environmental impacts, produce less secondary waste, and have the potential to meet future economic and societal needs in a more sustainable manner than conventional energy sources like fossil fuel [2]. Furthermore, Saidur et al. [73] claimed energy produced by wind turbines does not produce pollutants like other sources of energy (e.g., coal, gas, and petroleum based fuel). Due to environmental, economic, and social benefits, wind energy is considered a promising renewable energy source. Therefore, undertaking a life cycle impact assessment is important in order to identify the burdens associated with wind power plant construction, use, and decommissioning. Life cycle assessment (LCA) is a method to assess the environmental impacts of a product from raw material acquisition through production, use, and end-of-life scene (i.e., cradle to grave) [15]. The LCA approach will be presented to investigate the environmental impacts of a wind park and to compare them with coal power plant impacts to quantify environmental impact trade-offs.

This paper will introduce a hypothetical new wind park to be located in northern Oregon. According to the U.S. National Renewable Energy Laboratory (NREL), Oregon has the potential for over 27,000 megawatts of installed onshore wind power [5]. There are a growing number of wind parks in northern Oregon, thus, examination of their environmental impacts using LCA is prudent. Because wind speed varies, annual power production is typically about 33% of the full turbine generating capacity [45]. For this reason, good site selection and turbine choice are critical to a commercial wind project success.

The intermittent nature of wind leads to fluctuations in energy production, and thus, requires some form of supplemental energy system. Baker et al. suggested a need for backup electricity generation to ensure grid reliability [74]. This study will examine the relative environmental impacts of wind energy when paired with supplemental energy sources to improve the environmental performance of electricity generation. Supplemental energy sources are selected based on existing sources in Oregon, which include biomass, hydropower, and natural gas [75]. A key motivating factor for the study undertaken in this research was to address the question about which energy source can most appropriately supplement with wind energy from an environmental perspective.

This work is an extension of an LCA study (Chapter 3), which explored the environmental impacts of wind turbines. As stated by Wang et al. [43], supplemental energy and energy storage can ensure the reliability of a wind park though out its use cycle. However, the question about whether supplemental energy or energy storage will be less impactful on the environment must be answered. In this study, we investigate the environmental impacts of potential supplemental energy sources using LCA. Part 2 of the study (Chapter 5) will investigate the environmental impact of energy storage to supplement wind energy.

The first section will look at how wind velocity data are used to select wind site. Although the five sites considered are located in the same region, they illustrate the differences in potential output and highlight the need to collect and analyze wind data for optimal investment in wind energy systems. Results of all calculations are then presented in a comparative manner. Several conclusions are then offered based on the analysis conducted.

4.2 Description of the wind park

Oregon is a state in the Pacific Northwest region of the United States. The geographical location of the state is favorable for wind power development due to the influence of the Pacific coastline and the wind pass along the Columbia River Gorge [75]. As of 2011, Oregon had a total installed wind turbine capacity of 2513 MW [76]. The Bonneville Power Administration (BPA) wind speed data used for this study is from five locations in northern Oregon (Augspurger, Biddle Butte, Hood River, Horse Heaven, and Roosevelt) for a period from February 2010 to January 2011 [77]. Wind speed data is collected using an anemometer located 21 meters above the ground.

4.3 Site selection

The wind turbines will be installed above the anemometer's height, which results in a higher wind speed. In order to calculate the increase in wind speed the power law method can be used, which has been derived empirically as the following [46]:

$$V = V_0 \left(\frac{H}{H_0}\right)^{\alpha} \tag{4.1}$$

where V_0 is the known wind speed at height H_0 (21 m), V is the wind speed at required height H (78 m), and α is the surface roughness. It is common to assume the surface roughness as 0.143 representing open plains, however, it has been found that 0.23 is an average value of α in northern Oregon [46].

Wind data for one year has been analyzed for each site to determine the site with the highest wind potential. The average monthly wind speed is calculated as follows [3]:

$$V_{avg} = \frac{1}{N}\left[\sum_{i=1}^{N} V_i\right] \tag{4.2}$$

where N is the number of records for each month and V_i is the wind speed for record i. The power produced by the wind per unit area (P_w) is given as [78]:

$$P_w = \frac{1}{2}\rho {V_i}^3 \tag{4.3}$$

where ρ is the air density in kg/m^3 and is given as $\rho = 1.225\ kg/m^3$.

Figure 4.1 shows the calculated monthly wind speed during the year at a height of 78 meters. Based on average monthly wind speed, the Augspurger region is selected as the best location to install a wind park. The wind speed is considered to be sufficient to produce electricity based on the average monthly wind speed data.

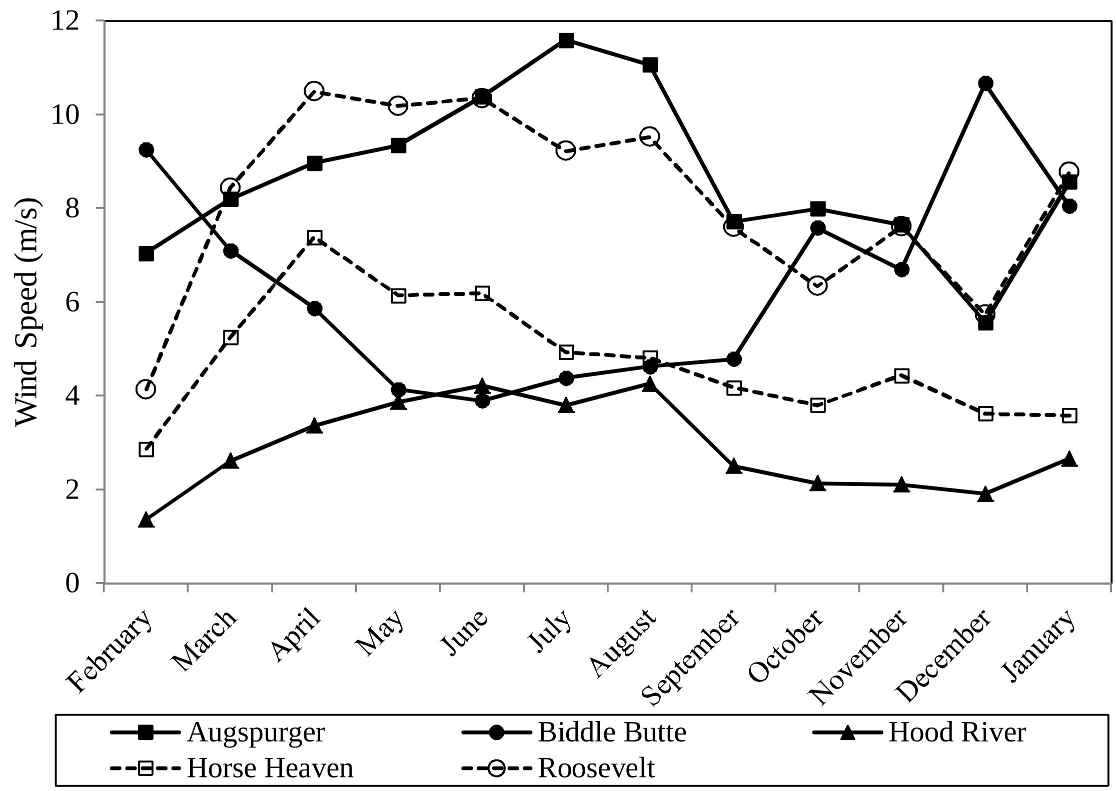

Figure 4.1 Monthly wind speeds at different locations from February 2011 to January 2012 (converted to 78 m height from [77]).

4.4 Problem description, goal, and scope definition

This study is based on a hypothetical wind park in northern Oregon that must provide an average of 200 MW. Thus, assuming a 35% capacity factor, 290 2.0

MW wind turbines are needed. Data regarding the manufacturing, transportation, operation, and decommissioning of the wind turbine are provided in the first manuscript (Chapter 3).

The goal of this study is to determine the least environmentally impactful supplemental energy sources among three options (i.e., hydro power, biomass, and natural gas) using the LCA approach. LCA is a method used to assess environmental aspects and impacts of products. Environmental impacts generated by all parts of a product's life cycle, from acquisition of materials through manufacture to recovery or disposal, are considered [13], [14].

The scope and system boundary of this study are presented in Figure 4.2. The wind park lifetime is assumed to be 20 years. A functional unit of 200MW over 20 years is used as a baseline for the comparison between the wind park with supplemental energy sources and a coal power plant.

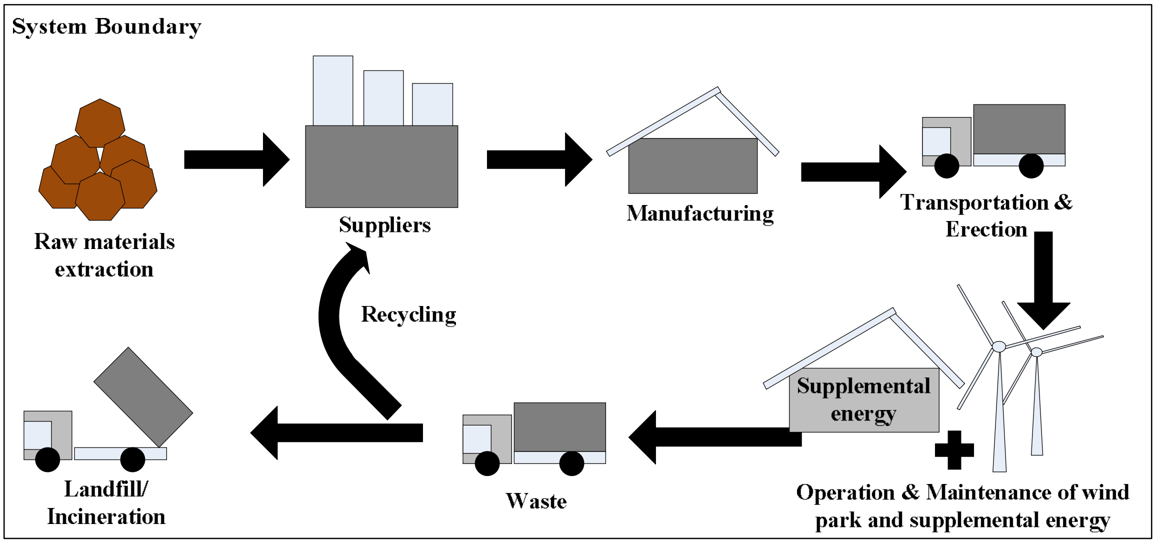

Figure 4.2 Life cycle assessment scope and system boundary.

4.5 Life cycle inventory

The selected wind turbine component information was gathered from a turbine manufacturer and reported in a past study (Chapter 3) [71], [72]. Supporting facilities are included in the analysis and based on a wind project report [79], as described below.

4.5.1 Wind park supporting facilities

A power collection system is used to transport the power from the wind turbines to the substation. It assumed to be comprised of 100,000 meters of copper electrical cable. The substation is comprised of a transformer, switching equipment, and a parking area as show in Table 4.1.

Table 4.1 Substation materials [79]

Material	**Weight (Ton)**
Steel	91.8
Copper	24.0
Lubricant oil	37.8
Fiber glass reinforced plastic	5.17
Wood board	5.17
Porcelain	5.17

The operations and maintenance facility is assumed to be a 464 square meter building. It has an office, workshop areas, and a control room. For this study, it will also be assumed to have sufficient space for the supplemental energy equipment.

Access roads would connect to graveled turbine pad areas at the base of each wind turbine. Crushed gravel roads are assumed to be 2 meters wide and 50 km in overall length.

4.5.2 Transportation and installation

Transportation of all turbine parts is considered from each manufacturer to the wind site. Transportation of raw material to the component manufacturers has been ignored because this information could not be acquired. Transportation distances have been estimated from the component manufacturers to the site as shown in Table 4.2.

Table 4.2 Transportation distances from supplier to erection site

Component	**Wind Turbine Supplier** (Distance)
Blades	Windsor, CO (1945 km)
Rotor	Brighton, CO (1931 km)
Gearbox	Lake Zurich, IL (2782 km)
Generator	Raleigh, NC (3826 km)
Yaw/Pitch system	Hebron, KY (3181 km)
Tower	Pueblo, CO (2205 km)
Nacelle	Brighton, CO (1931 km)

4.5.3 Operation and maintenance

Just like any other energy system, wind turbines must be serviced regularly and, in the case of failure, repaired. For the major components, it is assumed to have maintenance every six months, which included visual inspection of the rotor blades, shafts and gearbox, and oil changes for the gearbox and hydraulic system. The operation and maintenance (O&M) process also considers the impacts from transportation of maintenance vehicles to the turbine site.

4.5.4 Supplemental energy sources

The information regarding biomass, hydropower, and natural gas plants are provided in the LCA software (SimaPro 7) database. The system boundaries of each source are defined as follows and presented in Table 4.3:

Natural gas: The process model includes fuel input, natural gas firing, and transportation. Electricity generation is accomplished by the combustion of natural gas.

Hydropower: This model describes the average operation of a representative dam with a height of more than 30 meters. It includes the area occupied and an estimation of greenhouse gas emissions out of the water reservoir and lubricant oil.

Biomass: Biomass production is represented by a poplar tree plantation with a seven-year growing cycle. Electricity generation is accomplished by gasification of biomass followed by combustion in a gas turbine. The process includes fuel and material extraction, the biomass production, biomass gasification power plant, and transportation.

Table 4.3 Life cycle inventory for supplemental energy sources (20 years)

Sources	Component	Amount	Process Model
Natural Gas	Natural gas	20673600 MWh	Natural gas,burned in power plant/US with US electricity U
	Natural gas power plant	1 plant	Gas power plant, 100MWe/RER/I US electricity U
Hydropower	Hydroelectric dam	20673600 MWh	Electricity, hydropower,at reservoir power plant/CH with US electricity
Biomass	Hardwood chips	2360 m^3	Wood chip, hardwood, u=80%, at forest/RER with US electricity U
	Biomass power plant	20673600 MWh	Electricity,biomass, at power plant NREL/US

4.6 Life cycle impact assessment method

This study presents a LCA of a wind park with supplemental energy generation and using method in analysis are ReCiPe 2008. The LCA is modeled using SimaPro, a software tool for LCA. ReCiPe 2008 is an internationally recognized impact assessment method [19]. It balances impacts across three damage types (i.e. Egalitarian, Hierarchist, and Individualist) from different archetypical perspectives to account for variation in impact valuation and modeling uncertainties. The Hierarchist (H) archetype with an average weighting set between the balance of short and long term perspectives, was selected. The ReCiPe method evaluates the impact in eighteen categories as follows: fossil depletion (FD), metal depletion (MD), natural land transformation (NT), urban land occupation (UO), agricultural land occupation (AO), marine ecotoxicity (ME), freshwater ecotoxicity (FE), terrestrial acidification (TA), climate change ecosystems (CCE), terrestrial ecotoxicity (TE), ionizing radiation (IR), Freshwater eutrophication (FEU), particulate matter formation (PM), photochemical oxidant formation (PO), water depletion (WD), human toxicity (HT), ozone depletion (OD), and climate change human health (CCH). One thousand ReCiPe points is equivalent to environmental impact generated by one European citizen over the course of a year [19].

4.7 Environmental impact assessment

Once all the material information for the wind park and supplemental energy sources were input to the LCA software, the environmental impact assessment could then be performed using several methods. This study first investigated the environmental impacts of a new wind park, followed by an assessment of the wind park when paired with supplemental energy sources. The results are presented below.

The life cycle environmental impacts of the wind park are presented in Figure 4.3. It shows the impact of various stages in wind park life cycle based on impact categories. Negative impact represents avoided impact or a benefit to the environment. Significant proportions of impacts are from the manufacturing stage of wind turbines. However, there is a significant benefit associated with the end of life stage. This demonstrates that wind turbines can partially offset their other impacts across their life cycle and they have the potential to create a negative emission balance when also considering benefits of their use phase over conventional energy sources. An impact of 26.8 MPt from the turbine manufacturing faces an offset of 9.8 MPt during the wind park end of life. It can reduce the environmental impact of the entire life cycle by 36.56%. Both O&M and T&I produce a low level of impact 0.003 and 0.394 MPt, respectively.

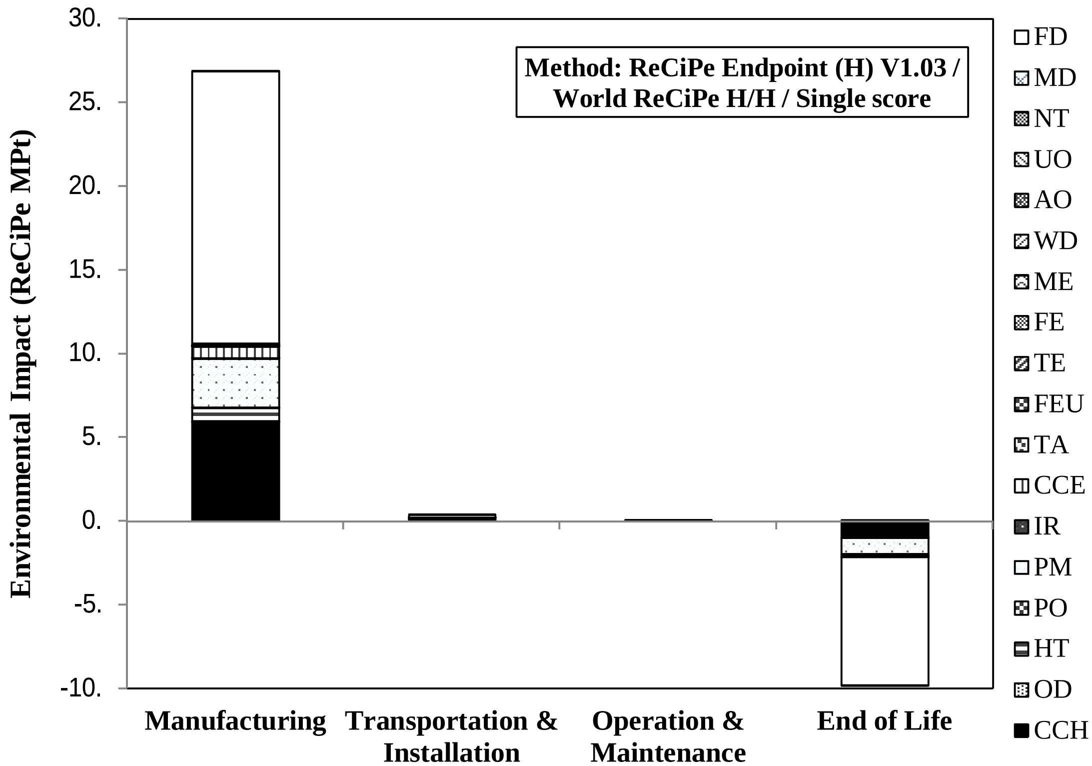

Figure 4.3 Environmental impacts of a wind park over its life cycle

Figure 4.4 shows the environmental impacts of the wind park paired with biomass, hydropower, and natural gas in comparison with a coal power plant. It is apparent that a coal power plant has the largest environmental impact (1.38 GPt) over 20 years. The impact of the wind park paired with biomass, hydropower, and natural gas is 0.08, 0.03, and 0.69 GPt, respectively. The main contribution is from the fossil depletion (FD) and climate change human health (CCH) categories. The environmental impact of the wind park and hydropower is 97% lower than the impact of the coal power plant. It can be concluded that the combination of the wind park and is the best supplemental energy source of the three considered in terms of environmental impacts.

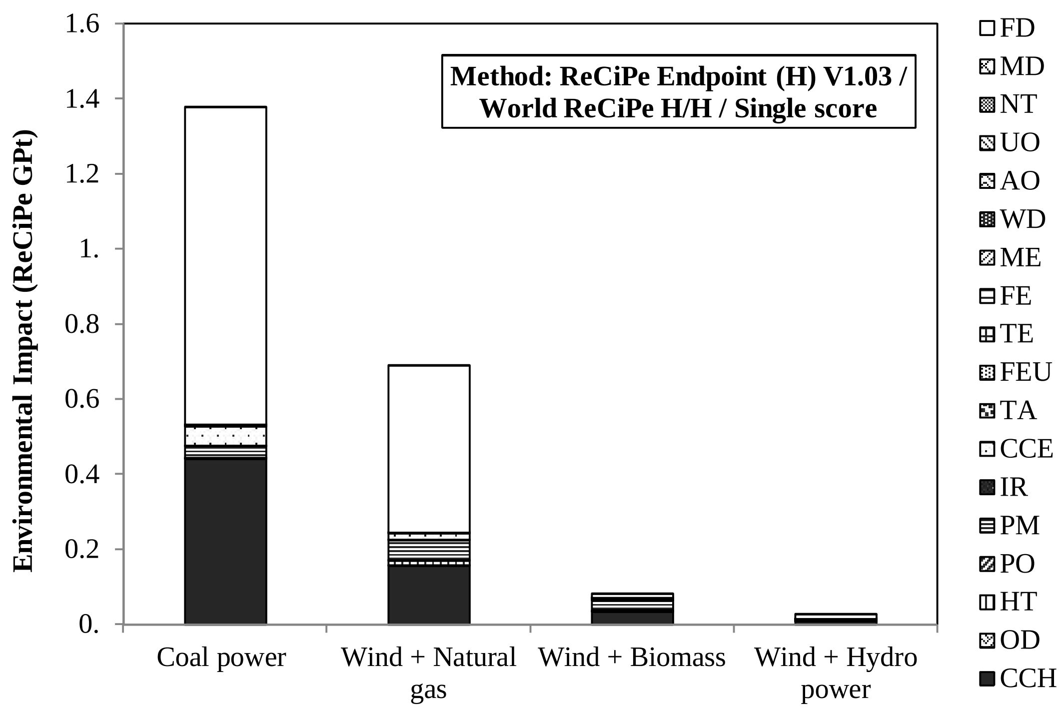

Figure 4.4 Environmental impact of each scenario

4.8 Summary and conclusions

The work presented demonstrates a life cycle assessment (LCA) of a hypothetical wind power plant and potential supplemental energy sources to be located in northern Oregon. The objective of this study is to assess the environmental impacts of wind energy with supplemental energy and to compare them with the same level of coal energy. In comparison to previous research, this work focused on understanding the impacts of supplemental energy when use in combination with a wind park, rather than impacts for a single wind turbine.

It was observed that wind turbine manufacturing has the greatest effect on the life cycle impacts of the wind park. Three supplemental energy sources, biomass, hydropower, and natural gas were compared from a life cycle perspective. Hydropower was found to be superior in terms of environmental impact with biomass power as the second best option. Overall, wind energy and supplemental energy sources were found to release lower environmental impacts than coal-based energy. The differences between the relative performances are significant enough to choose hydropower as the suitable supplemental energy for the hypothetical wind park.

From this study, it is evident that wind energy cannot replace an entire segment of coal power without supplemental energy. An implication of this study is that standard LCA approaches can be used for evaluating a wind park and supplemental energy sources in terms of their environmental impact. This is particularly important as operators seek for ways to generate revenues by expanding wind energy generation, while also striving to reduce environmental impacts of their operations.

CHAPTER 5 – ENVIRONMENTAL IMPACT OF WIND ENERGY IN NORTHERN OREGON - PART 2: SUPPLEMENTAL ENERGY STORAGE (ZINC-BROMINE BATTERY)

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Abstract

Renewable energy, such as wind energy, has the potential to reduce dependence on fossil fuels in the electrical energy sector, however, wind energy is inherently intermittent and fluctuating. Thus, the deployment of supplemental energy and energy storage is becoming an essential component of future wind park development for electrical grid quality. The aim of this study is to analyze the environmental impacts of a wind park with energy storage. A complementary study examines the environmental impacts of a wind park with supplemental energy generation (Chapter 4). A zinc-bromine battery is selected as the supplemental energy source for the wind park. Life cycle assessment (LCA) is applied to quantify the environmental impacts of a hypothetical wind park and zinc-bromine battery facility. The analysis considers the entire life cycle from cradle to grave for both systems. Results indicate that the environmental impacts from the wind park and zinc-bromine battery are lower than the impacts from coal power generation but greater than the impacts of wind energy with supplemental energy generation from biomass, hydropower, and natural gas.

5.1 Introduction

Wind energy has variable and uncertain output, are unlike the dispatchable sources used for the majority of electricity generation in the United States. The variability of wind energy has led to concerns regarding the reliability of an electrical grid that derives a large fraction of its energy from these sources as well as the cost of reliably integrating large amounts of variable generation into the electric grid [24]. Because the wind is not consistent for any given location, there has been an increased call for the deployment of energy storage as an essential component of future energy systems that use large amounts of wind and other variable renewable resources [21].

One factor in installing energy storage is the size or total quantity of energy which must be stored. This will be fixed by the power to be delivered and the maximum length of windless period during which the battery is expected to operate [31]. While energy storage is very important in ensuring the reliability of power delivery, the type of energy storage that can be used and the economics of energy storage are beyond the discussion of this paper. This paper focuses on the environmental impact of energy storage for the hypothetical wind park described in Part 1 of this study (Chapter 4). The energy storage option presented is a zinc-bromine battery.

5.2 Background

The zinc-bromine battery is a flow battery or circulated system [80]. The zinc-bromine battery system consists of a reactor stack, electrolyte reservoirs, and an electrolyte circulation system (pumping system). The electrolytes are pumped though a reactor stack and back into the tanks when the battery is charged or discharged [32]. A schematic diagram of the battery system is shown in Figure 5.1. The predominantly aqueous electrolyte is composed of a zinc bromide salt dissolved in water (Zn^{2+}(aq) and Br^-(aq)). During charging, metallic zinc (Zn(s)) is plated from the electrolyte solution onto the negative electrode surfaces in the cell stacks. Bromide (Br^-) is converted to bromine (Br_2) at the positive electrode surface of the cell stack and immediately stored as a safe, chemically complexed organic phase in the electrolyte tank [81]. The reactions involved in the battery process are as follows:

$$Zn(s) + Br_2(aq) \rightleftharpoons Zn^{2+}(aq) + 2Br^-(aq) \tag{5.1}$$

The function of the bromide complexing reagent is to lower the concentration of bromine in the catholyte by extracting bromine into a water-immiscible phase that acts as a bromine storage medium. This allows high energy storage capacity at a low rate of self discharge.

The primary features of zinc-bromine battery are 100% discharging capability, high energy density, and no shelf life limitations [31]. In effect, zinc bromine can be left fully discharged indefinitely without damage. It has the ability to store energy from any electricity generating source.

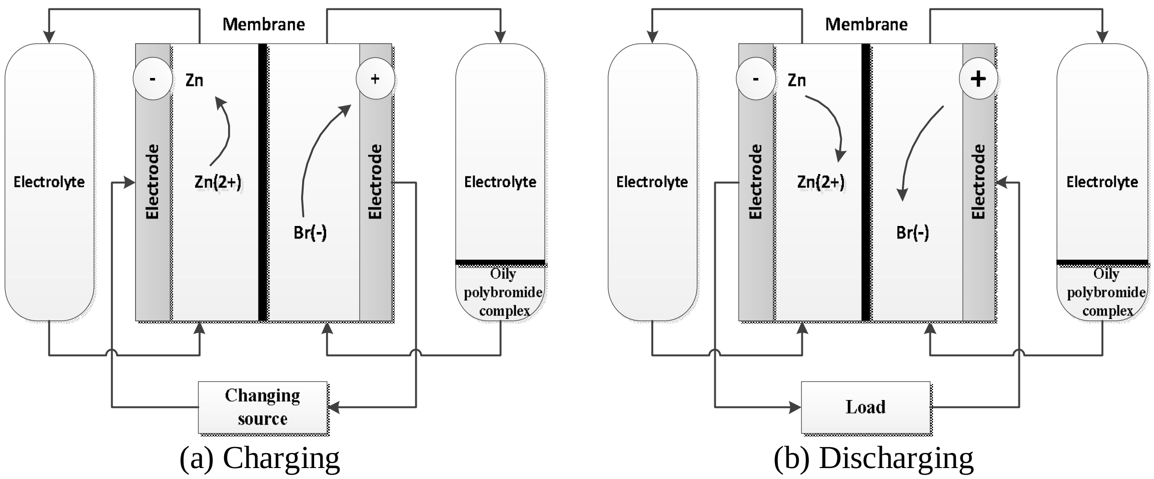

Figure 5.1 Conceptual diagram of a zinc-bromine battery (a) charging and (b) discharging.

5.3 Battery Sizing

In its simplest form, the power of the combined ZnBr battery and wind park is dispatched to the electrical grid to supply a set amount of power. However, this assumes that the state of operation of the wind turbine generators is always relatively near that of the set point and neglects the limitations of the different converters. Furthermore, in certain cases, the storage device may not be used effectively, particularly when there is a large mismatch between the set point power and the output of the wind park. For a wind generator, the operating point is constantly varying since the energy source is dependent on the local environmental conditions. By allowing the set point to vary, the time scale over which the storage device can be applied is extended, thereby maximizing the benefits of the storage, while relinquishing only slightly the firm regulation of the output power. Through a proper design of the energy management system, the storage device can be kept in operation by curtailing or boosting the power reference, near the upper or lower storage limits.

In order to find the suitable battery size, equations 5.2-5.5 are used. These calculations neglect energy losses (e.g. in the power switches). Equation 5.4 is to calculate the energy, which will store in battery from the excess wind energy. Equation 5.5 is to calculate the amount of energy remain in the battery storage.

$$E_{Storage_{(i)}} = E_{w_{(i)}} - E_{Demand_{(i)}} \tag{5.2}$$

$$E_{Energy\ Level_{(i)}} = E_{Energy\ Level_{(i-1)}} + E_{Storage_{(i)}} \tag{5.3}$$

where $E_{W_{(i)}}$ is the energy produced by the wind park at timestep i. $E_{Demand_{(i)}}$ is the grid energy demand over timestep i (assumed constant over time). $E_{Storage_{(i)}}$ is the amount of energy entering the battery over timestep i. $E_{Battery}$ is the battery energy storage capacity. $E_{Energy\ Level_{(i)}}$ is the energy level in the battery at timestep i. Equation 5.4 and 5.5 are the constraints in finding the battery size.

$$\sum_{i=0}^{n}\left(E_{W(i)} - E_{Demand(i)} + E_{Energy\ Level(i-1)}\right) \geq 0 \tag{5.4}$$

$$\sum_{i=0}^{n}\left(E_{W(i)} - E_{Demand(i)} + E_{Energy\ Level(i-1)}\right) \leq E_{Battery} \tag{5.5}$$

Equation 5.4 shows the summation of wind energy produced at time i must be larger or equal to zero. It will ensure the stability of electricity send to the grid and the remaining energy in the battery. Equation 5.5 restricts the maximum battery energy level to be less than or equal to the battery capacity.

Figure 5.2 demonstrates the energy state of the battery over time and assumed constant supply/demand over each 5 min period. The grid energy demand is stable at 60 GJ. During time periods when wind energy is unable to meet the energy demand, energy from battery will supplement wind energy. At time periods when wind energy produces more than the energy demand, the battery will be charged.

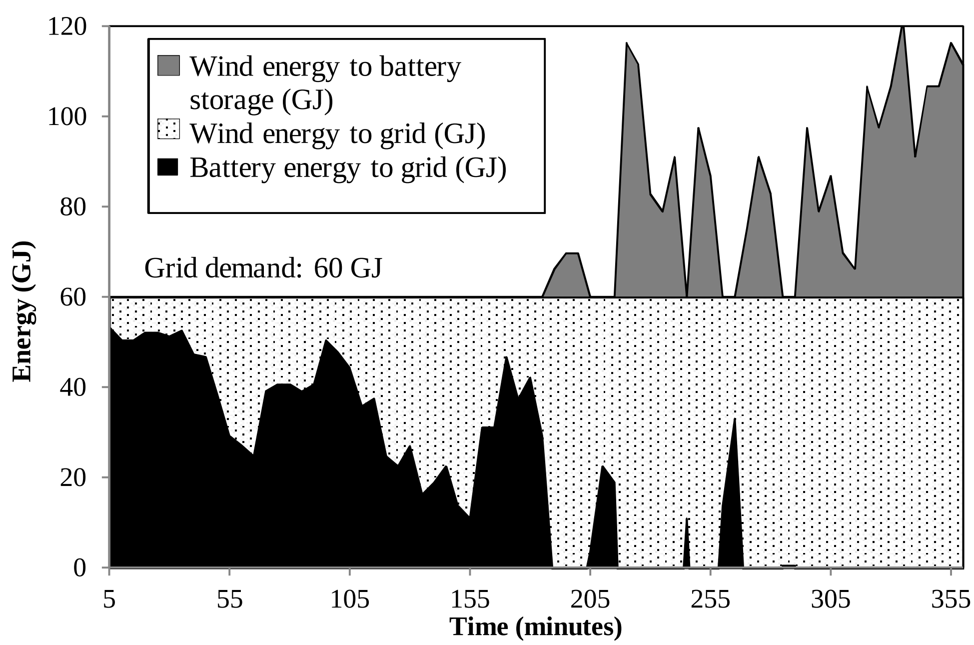

Figure 5.2 Battery charging and discharging profile for a period of time.

Using the method described above, 20 MWh of battery capacity is required to supplement a 200 MW capacity, wind park located in Augspurger, Oregon. Thus, 400 units of a 50 kWh ZnBr battery cell are needed.

5.4 Life cycle methodology

In order to assess relative environmental impacts and identify potential future research needs of wind energy generation, the life cycle assessment (LCA) method was applied. The LCA study was facilitated using a commercially available software tool (SimaPro 7). In general, an LCA study is completed in four stages [12] : (1) Define the goal and scope, (2) Conduct a life cycle inventory analysis, (3) Conduct a life cycle impact assessment, and (4) Interpret results.

5.4.1 Goal and scope definition

The goal of this LCA study is to identify the environmental impacts of a wind park utilizing supplemental energy storage to meet demand during low wind periods. The scope and system boundary of this study are presented in Figure 5.3, and consider wind turbine and battery production, transportation, construction, operation and maintenance, and disposal stages. This work builds upon a life cycle assessment of a 2 MW wind turbine (Model 2) in Chapter 3. The LCA is performed using the ReCiPe impact assessment method.

As basis for comparison, the lifetime of 20 years was selected. A functional unit of 1928 GWh of energy produced is used as a baseline for the comparison between the wind park with energy storage and a 200 MW coal power plant. This study has been divided into two scenarios, a wind park paired with a zinc-bromine battery and a coal power plant.

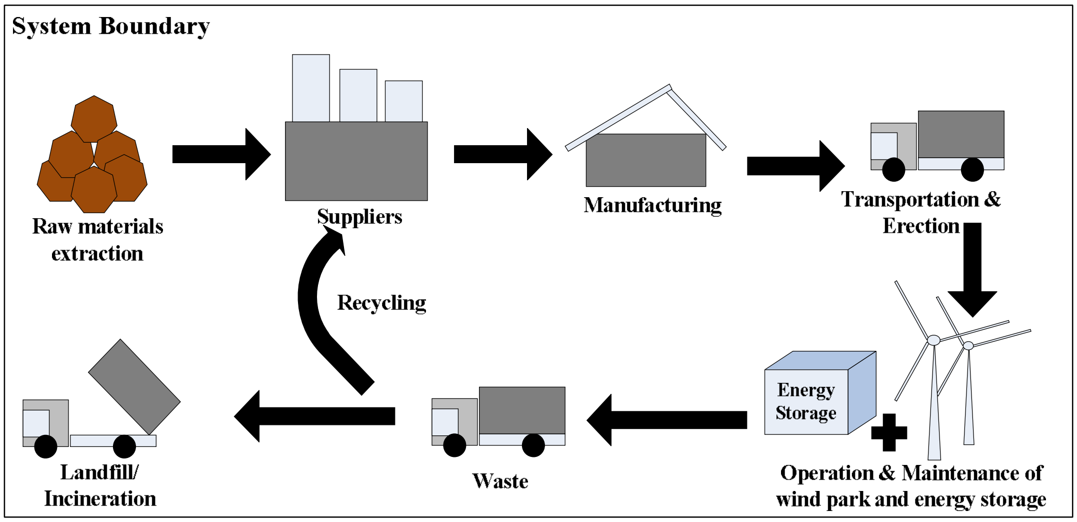

Figure 5.3 Life cycle assessment scope and system boundary.

5.4.2 Life cycle inventory

Raw material inventory data for the wind park is based on the previous study in Chapter 4. The material inventory data for the ZnBr battery are presented in Table 5.1. Due to the limitation of LCA databases, some of electrolytes are modeled using chemicals that have similar production processes. In this study, bromide is modeled as chloride. The disposal stage of the battery only considers the battery container. The disposal of electrolyte will be neglected because the lack of information of chemical waste management and potential for reclamation.

Table 5.1 Zinc-bromine battery material inventory

Material	Weight (kg)
Electrolyte	
Zinc Bromine	240000
Zinc Chloride	43000
4-Methylmorphaline	130000
Bromoethane	160000
Tetrahydrofuran (THF)	13000
Hexanes	23400
Water	360000
Bromine	3600
Container	
Enclosure - Steel	274.00
Fuel Cell - PTFE	10.37
Electronic Box - Steel	13.43
Liquid Container - PTFE	36.52
Tubing - Viton	0.63
Wire - Copper	15.60

5.5 Environmental impact assessment

All the material information for the wind park and supplemental energy storage were compiled in the LCA software, which facilitated environmental impact assessment. One impact assessment methods is ReCiPe 2008, an internationally recognized impact assessment method. It balances impacts across three damage types from different archetypical perspectives, i.e., Egalitarian, Hierarchist, and

Individualist, to account for variation in impact valuation and modeling uncertainties. The Hierarchist (H) archetype with an average weighting set, which balances short and long term perspectives, was selected. The ReCiPe method evaluates the impact to eighteen categories as follows: fossil depletion (FD), metal depletion (MD), natural land transformation (NT), urban land occupation (UO), agricultural land occupation (AO), marine ecotoxicity (ME), freshwater ecotoxicity (FE), terrestrial acidification (TA), climate change ecosystems (CCE), terrestrial ecotoxicity (TE), ionizing radiation (IR), Freshwater eutrophication (FEU), particulate matter formation (PM), photochemical oxidant formation (PO), water depletion (WD), human toxicity (HT), ozone depletion (OD), and climate change human health (CCH). One thousand ReCiPe points is equivalent to the environmental impact generated by one European citizen over the course of a year [19]. The results of the study are presented below.

Figure 5.4 presents the environmental impact of the wind park with ZnBr battery in each impact category compared with coal power. It appears that fossil fuel depletion, climate change-human health, and particulate matter formation cause the greatest impact, respectively. The main contribution of fossil fuel depletion impact is from steel in the wind turbines and chemical compound of the zinc-bromine battery. The contribution of impacts from the wind park with a supplemental ZnBr battery can be significant, but it can be seen that coal power has 6 times the overall environmental impact (Figure 5.5).

It can be concluded that the combination of a wind park and ZnBr battery would be a suitable replacement for coal power from an environmental perspective. Overall, ZnBr battery storage is unable to compete with hydropower and biomass as supplementary storage options. It can be concluded that wind park with hydropower appears to be the best supplemental energy system from an environmental perspective.

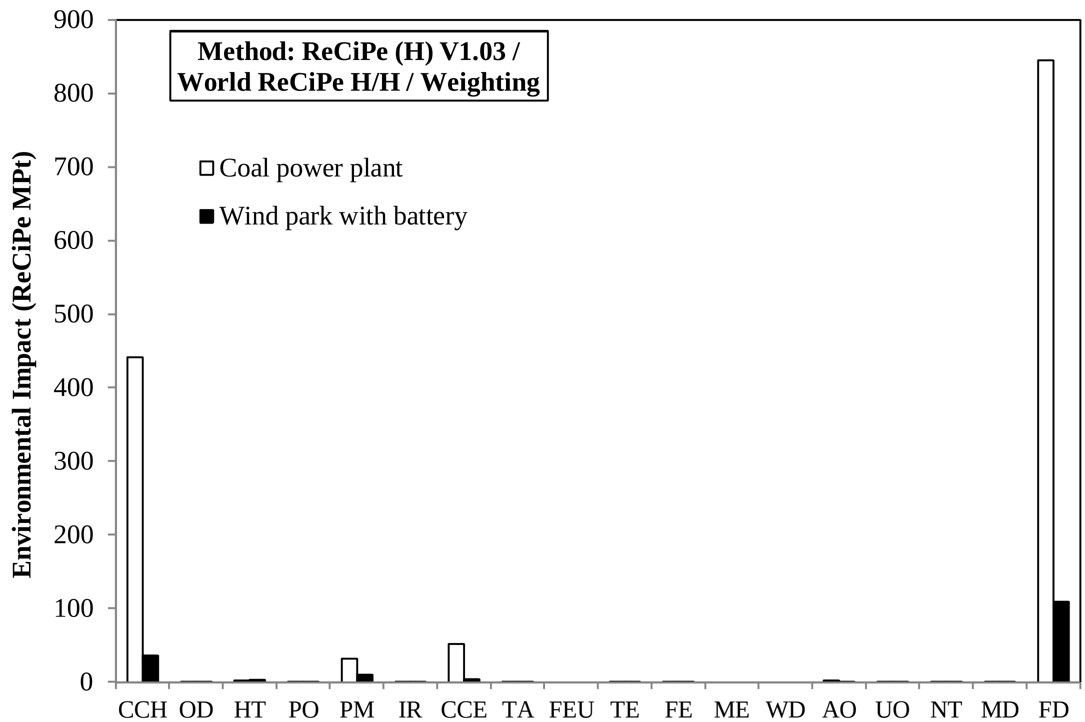

Figure 5.4 Environmental impact of the wind park with ZnBr battery compared to coal energy for selected impact categories.

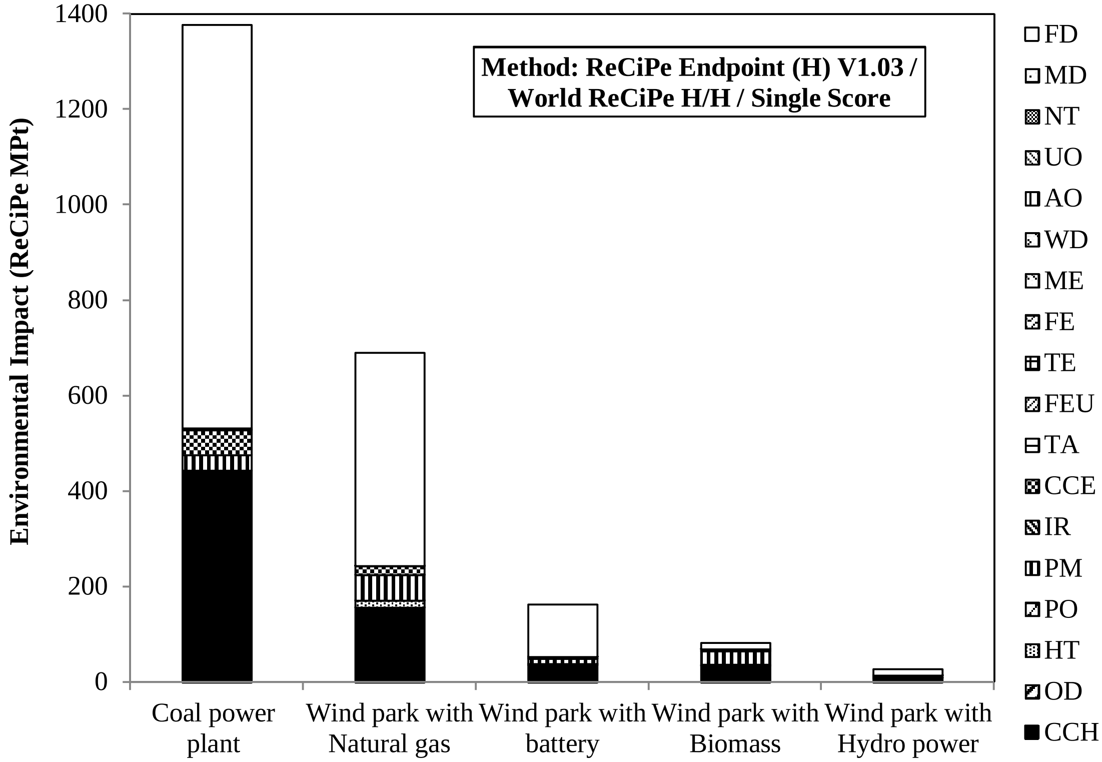

Figure 5.5 Environmental impacts of coal power plant compared with a wind park and selected supplemental energy systems

5.6 Summary and conclusions

The aim of this study was to assess the environmental impacts of a wind park with supplemental battery energy storage and to compare the impacts to those for a coal power plant. The results showed the wind park with battery energy storage has lower impact than coal power plant. Furthermore, when the results of this study are compared with the previous study (Chapter 4), it can be found that the environmental impact of wind park and hydropower is predicted to have lower impacts than coal power and a wind park with the supplemental energy systems investigated (i.e., biomass energy generation, natural gas energy generation, and ZnBr battery storage). Complementing wind energy with energy storage has been considered a viable option, but further technology development must be prior to wider adoption due to costs and potential environmental impacts. This study shows environmental improvement is needed in order to justify the associated expense and thus such storage systems will need to provide a marked improvement in the overall performance of wind park reliability. In addition, the improved performance could be mandated by utilities through interconnection requirements; otherwise, there may be little motivation to consider broader impacts than associated costs.

When comparing environmental impacts, the decision to implement supplemental energy storage is not competitive with the option to install supplemental energy generation. The decision maker must decide whether the environmental benefits are worth the investment. At this point, it is worth making a reminder that the percentage of those impact offset from the impact of coal power plant is huge enough for benefit. The result of this study may serve as a base line for a wind park to meet the energy demand for minimal environmental impact.

CHAPTER 6 – SUMMARY AND CONCLUSIONS

In this chapter, the research undertaken as a part of this thesis is reviewed and the conclusions are summarized. The research contributions, limitations, and recommendations for future work are presented.

6.1 Summary of the thesis

Increasing global population, quality of life, and affluence have yielded a significant increase in energy consumption. While energy can be generated in a number of ways, including use of renewable resources, the primary resources for generating the majority of needed energy comes from non-renewable resources, e.g., fossil fuels, which are accompanied by a number of environmental impacts that are endangering the current generation and threating the well-being of future generations. Greenhouse gas emissions represent one challenge and have been reported to be a primary contributor to climate change.

The research explored in this thesis helps provide a better understanding of the effect of wind energy and associated supplemental energy systems on the environment through a cradle-to-grave life cycle perspective. Research tasks explored the environmental impacts of a wind turbine and what is the most suitable supplemental energy system for a hypothetical wind park in northern. A comprehensive review composed largely of recent research literature identified current research needs and supported the novelty of this work. It pointed out the need to perform a life cycle assessment (LCA) study using US data, as well as the need to implement a supplemental energy system for the wind park. LCA methodology was introduced as a method to quantity environmental loading across the entire life cycle of a product or system. The International Organization for Standardization (ISO) has standardized an LCA framework that consists of four elements: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. The life cycle impact assessment (LCIA) methodology used in this research is ReCiPe 2008, which comprises harmonized category indicators from CML 2000 and Eco-indicator 99. These impact indicators serve as a means for systematically quantifying the relationship between the product and the environment.

An LCA of wind turbines was conducted and composes Chapter 3 (manuscript 1). Two wind turbine models were selected for comparison. Both wind turbine models were determined to be favorable power generating systems. When compared based on environmental impacts, Model 2 was determined to have a lower measure of environmental impact, due to its lower level of required material inputs and transportation distance from the component manufacturer to the wind park.

Chapter 4 (manuscript 2) examined the environmental impacts of a wind park when implementing various supplemental energy generation systems. This study first conducted a wind park site selection process considering five locations in northern Oregon: Augspurger, Biddle Butte, Hood River, Horse Heaven, and Roosevelt. Of these, Augspurger was identified as the location with the highest average wind speed for a one year time period. A hypothetical 200 MW wind park was analyzed with the supplemental energy systems (i.e., biomass, hydropower, and natural gas power generation). A wind park paired with hydropower generation was found to be the best candidate with regard to environmental impacts.

Chapter 5 (manuscript 3) shared a similar objective to Chapter 4, which was to investigate the environmental impact of a wind park with a supplemental energy system, though it focused on energy storage (ZnBr battery), rather than energy generation. An analysis was conducted to determine an appropriate battery capacity to supplement the wind park. Battery capacity determined the material consumption of the ZnBr battery. Thus, it was assumed the wind park would use 400 of 50 kWh ZnBr batteries. The environmental impacts of a wind park with ZnBr battery were compared to other options and it was found that the impact from coal power resulted in much higher impacts than the wind park/ZnBr battery scenario, as well as the other options considered.

Overall, supplemental energy is necessary to ensure electrical power quality of a wind park but it leads to uncertain life cycle environmental impacts and costs. For reducing environmental impacts of alternative energy sources, energy utilities must carefully consider regional opportunities. The Pacific Northwest is ideally suited for supplemental biomass and hydropower, which also appear to be lower environmental impact options than ZnBr battery storage and supplemental natural gas power.

6.2 Conclusions

This research examined the differences in environmental impacts of two wind turbine models and for a wind park with supplemental energy systems (biomass, hydropower, natural gas, and zinc-bromine battery). Life cycle assessment (LCA) was the methodology implemented for this environmental analysis. Several key learnings have been discovered about the environmental impacts for the implementation of supplemental energy systems with a wind park. The following are the substantial conclusions which have been drawn from the research:

1. The manufacturing stage is the most impactful in the life cycle of wind turbine. Also, geographical location of production is an influential factor in the environmental load of wind turbine manufacturing.
2. Electricity generation from fossil fuel depletes natural resources and produces greenhouse gas emissions. These concerns have caused many to lean toward renewable energy sources that can provide the same energy, reliability and stability. Wind energy alone cannot meet these requirements. When wind is combined with other types of electricity generation sources, however, it becomes a viable alternative and provides a power source that is equivalent to a fossil fuel power plant with less environmental load.

3. Combining wind energy with supplemental energy storage is a promising technology for improved renewable energy reliability. Even though energy storage is impactful over its life cycle, impacts are reduced by 70% when compared to the impacts of fossil fuel energy.

6.3 Contributions

The work undertaken within this thesis has focused on the environmental impact assessment of wind energy and supplemental energy systems. Contributions of the research are as follows:

1. Manuscript 1 is the first reported study to investigate the relative environmental impacts of two similar turbine designs in the US. Prior work has compared turbines of dissimilar size or technological basis (e.g., a geared and gearless turbine). In addition, it is the first known study to consider the impacts of the supply chain and wind turbine design variation simultaneously. In terms of environmental decision making, this study provides an approach for selecting the wind turbine design which use less material and supply chains with shorter transportation distances (depending on the wind park location).
2. Manuscript 2 investigated the environmental impacts of a wind park with supplemental energy, and is the first reported to study the environmental impact of both as one system. This study offers an approach and initial

results to substantiate that wind paired with other renewables is less impactful than fossil sources, even if paired with wind energy.

3. Manuscript 3 is the continuation of manuscript 2 and investigated the environmental impacts of a wind park with supplemental energy storage. This work is the first to report the environmental impact of a wind park with supplemental energy storage. This study demonstrated that wind and ZnBr battery storage offer a less environmentally impactful option than coal power when supplemental renewable sources are not available.

6.4 Future Work

The work carried out in this thesis focused on life cycle assessment of wind energy with supplemental energy systems. The following are suggestions for future research:

1. Explore varying energy demand: The current work considered a 20 year life time, assuming steady state grid energy load conditions. Energy consumption is expected to increase and the energy mix is expected to change over time. These time varying effects on environmental performance should be investigated.
2. Explore additional supplemental energy systems: The work in this thesis focused on supplemental energy for a hypothetical wind park in northern Oregon. The supplemental energy selected is based on the available energy

resources. For other regions different resources are available which creates gaps in life cycle inventory data to assist environmental impact assessment.

3. Explore different types of energy storage: Many types of energy storage have been developed which rely on different fundamental operating principles materials, components, and systems. These energy storage systems have different cost, environmental impact, and performance characteristics, which will result in various tradeoffs that must be understood and analyzed.

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Appendices

Appendix A : Wind locations map